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Report of the Proceedings of the Colloquium and Workshop on Multiscale Coupled Modeling

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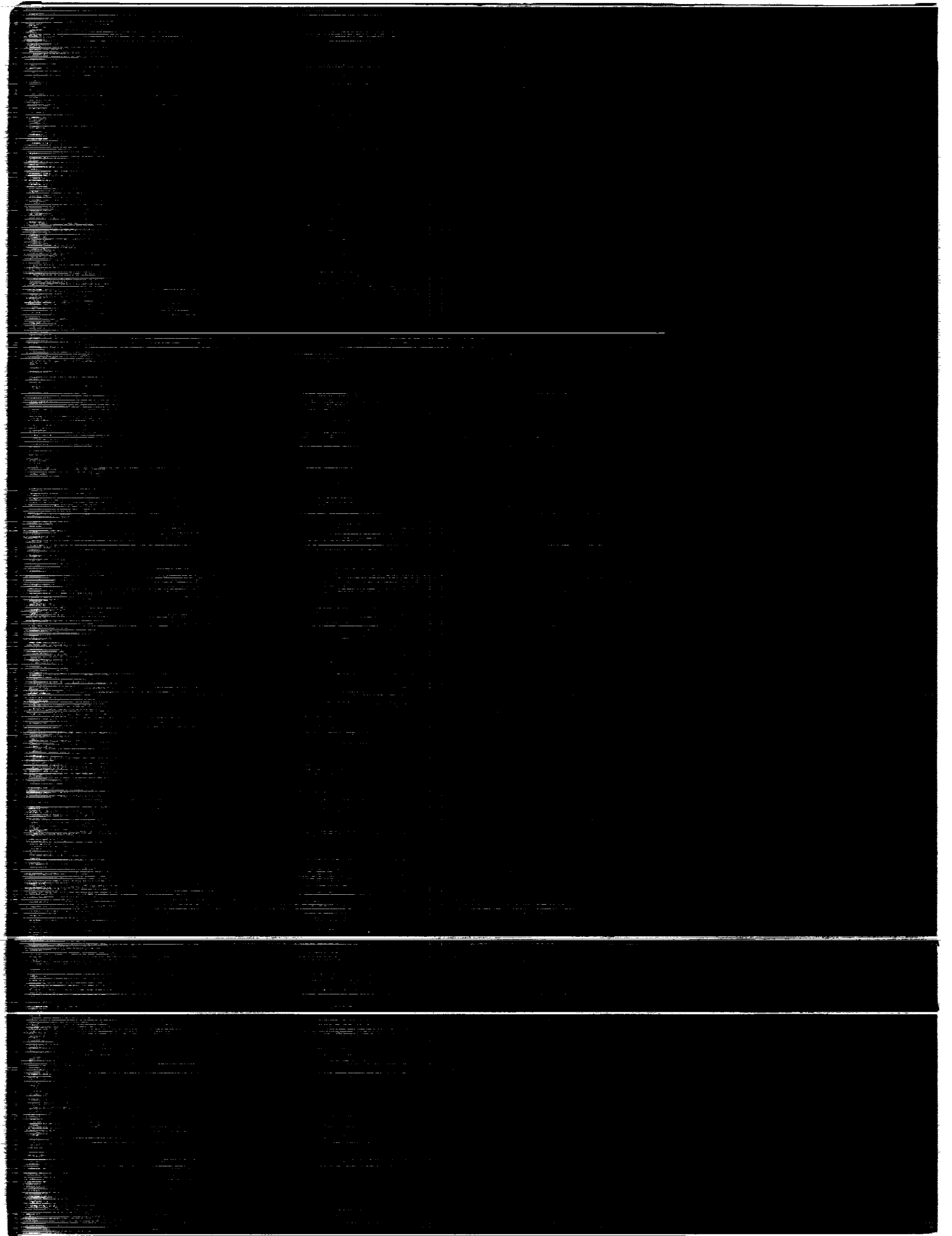

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Report of the Proceedings of the Colloquium and Workshop on Multiscale Coupled Modeling

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List of Acronyms

ACARS	Aircraft Communications Addressing and Reporting System
ARM	Atmospheric Radiation Measurement
ASOS	Automated Surface Observing System
AVHRR	Advanced Very High Resolution Radiometer
AWP	Aviation Weather Program
BATS	Biosphere-Atmosphere Transfer Scheme
BOREAS	Boreal Ecosystems Atmosphere Study
CaPE	Convection and Precipitation Experiment
CART	Clouds And Radiation Testbed
CASH	Commercial Aircraft Sensing of Humidity
CCOPE	Cooperative Convective Precipitation Experiment
CEES	Committee on Earth and Environmental Sciences
CINDE	Convection Initiation and Downburst Experiment
CLASS	Cross chain LORAN Atmospheric Sounding System
CME	Cooperative Multiscale Experiment
DIAL	DIfferential Absorption Lidar
FAA	Federal Aviation Administration
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
GCEM	Goddard Cumulus Ensemble Model
GCIP	GEWEX Continental International Project
GCM	Global Climate Model
GCSS	GEWEX Cloud Systems Study
GEWEX	Global Energy and Water EXperiment
GOES	Geostationary Operational Environmental Satellite
GVaP	GEWEX Water Vapor Project
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land-Surface Climatology Project
HIS	High resolution Interferometer Sounder
LES	Large-Eddy Simulation
MCC	Mesoscale Convective Complex
MCS	Mesoscale Convective Systems
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NEXRAD	NEXt generation weather RADar (also known as WSR88D)
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OSSE	Observing System Simulation Experiments
PBL	Planetary Boundary Layer
RADM	Regional Acid Deposition Model)
RASS	Radio Acoustic Sounding System
SAR	Subcommittee on Atmospheric Research
SESAME	Severe Environmental Storms and Mesoscale Experiment
SiB	Simple Biosphere model
SSM/I	Special Sensor Microwave/Imager
STATSGO	STATe Soil GeOgraphic database
STORM	STorm-scale Operational and Research Meteorology
STORM-FEST	STORM-Fronts Experimental Systems Test
USGS	United States Geological Survey
USWRP	United States Weather Research Program

Executive Summary

The Colloquium and Workshop on Multiscale Coupled Modeling was held for the purpose of addressing modeling issues of importance to planning for the Cooperative Multiscale Experiment (CME). The colloquium presentations attempted to assess the current ability of numerical models to accurately simulate the development and evolution of mesoscale cloud and precipitation systems and their cycling of water substance, energy, and trace species. The primary purpose of the workshop was to make specific recommendations for the improvement of mesoscale models prior to the CME, their coupling with cloud, cumulus ensemble, hydrology, and air chemistry models, and the observational requirements to initialize and verify these models.

Representatives from six meteorological programs each expressed a potential interest in collaborating together to achieve the unified purposes of the CME. Representatives from each of these programs discussed how their respective programs could benefit from participation in a fully scale-interactive, multi-disciplinary field program designed to increase understanding of Mesoscale Convective Systems (MCSs): (1) how scale-interactive processes generate and maintain MCSs; (2) the relative roles of balanced and unbalanced circulations in MCS dynamics; (3) the predictability of MCSs; (4) the role of MCSs in large-scale atmospheric circulations and the relationship of MCS occurrence to variations in large-scale flow; (5) what data bases are required to initialize and validate coupled cloud-resolving/mesoscale models, that may be further coupled with hydrological or chemical models; and (6) the optimal use of four-dimensional data assimilation to retrieve cloud and state parameters from remote sensing instrumentation.

The high frequency of MCS activity in the spring and summer months, the ability to transfer research results to the data-sparse tropical environment, and the availability of frequent, high density operational measurement systems in the central U. S. argue strongly to hold the experiment in this region. A cooperative experiment is needed, because even though the costs of implementing a multiscale experiment are reduced by the considerable observations already available there, the total additional observing systems needed to provide the necessary multiscale measurements are still quite expensive. Most convective field experiments in the past have attempted to resolve only the immediate scales of moist convection using network arrays that spanned two or three atmospheric scales at most. This has precluded a description of the entire life cycle of MCSs and their interaction with larger scale systems, the land surface, and trace species. Fortunately, observational, computer, and data assimilation advances now make it possible to simulate scale contraction processes from the synoptic scale down to the cloud scale, and interactions between complex meteorological, land surface, precipitation, chemical, and hydrologic processes with coupled, multiscale models. Thus, the time is finally right from a technical and observational perspective to conduct a multiscale, multi-disciplinary field experiment focused on the mesoscale convection problem. Since numerical models now have the capability to explicitly resolve features which are inherently scale-interactive, it is extremely important to muster all the scientific forces which have an interest in these problems to develop a multiscale field experiment that contains meaningful meteorological, hydrological, and chemical observing and modeling elements.

The colloquium covered the following topics: data assimilation and model initialization techniques, measurement and modeling of moist processes, parameterization of sub-grid scale convection, boundary layer, and radiation physics, coupled land surface/hydrologic/atmospheric models, mesoscale and cloud-scale chemistry modeling and measurement, mesoscale model validation, and techniques/resources for storm-scale numerical weather prediction. A major issue raised in the colloquium concerns precipitation data assimilation, in that there are serious problems in both assimilating techniques and the sources of hydrologic data. Knowledge of the three-dimensional mesoscale structure of the moisture field at frequent time intervals is the most crucial advance needed. No single existing observing system is capable of satisfying this requirement. The quality and interpretation of indirectly measured hydrologic cycle data need to be improved, in conjunction with the development of techniques to retrieve hydrometeors, which are needed to infer latent heating profiles from satellites and WSR-88D radars. At the convective scale, where the primary observing tool will be Doppler radars, there exist difficult issues surrounding the determination of initial conditions for all model variables from measurements of radial velocity and reflectivity in combination with other larger-scale data. The use of multi-parameter radar to initialize microphysical processes in coupled models should be investigated further. The use of variational approaches to data assimilation was reviewed also. These techniques are presently

constrained by significant computational and numerical issues, and it is not clear that such efforts will actually result in improvements in the assimilated state and resulting forecasts.

CME measurement strategies must extend well beyond the "visible" cloud boundaries, and must not be limited to the dynamically active stages of MCSs, but also include observations of "fossil" MCS residue. In fact, all the important sources and sinks of moisture associated with MCS genesis and evolution must be identified in three dimensions and with sufficient temporal resolution to be useful for developing, improving, and verifying sub-grid scale parameterization schemes. Hydrological cycle improvements are critically needed to not only produce accurate precipitation in all kinds of situations, but also to transport moisture vertically and to improve upon model treatments of clouds as they relate to the radiative budgets by using explicit prediction of condensate fields and knowledge in the initial state of the models of the cloud bases, tops, and optical properties.

Convection is much more of a multi-scale phenomenon than is commonly realized; experiments that have focused only on the structure of individual clouds or MCSs have not been able to resolve the nature of the processes that cause convection or to document the complete effects of convection upon larger scales. There are no existing data sets with sufficient temporal and spatial resolution to verify closure hypotheses contained in cumulus parameterization schemes. What is required is very high temporal resolution data over multiple scales to analyze complex interactions between clouds and the mass field, as well as in-situ measurements of thermodynamic properties and hydrometeors. The most critical process that needs to be determined is the rapid interaction between the clouds and the mass field on meso-beta through synoptic scales.

Very little is known about the influence of mesoscale variability on PBL and turbulence statistics, since the parameterization of boundary layer processes for use in larger scale models has been based almost exclusively on observations collected for horizontally homogeneous surface conditions under simple, slowly time-varying synoptic weather conditions. Another issue concerns how cumulus-induced subgrid-scale effects should be included. Stratus-type clouds and their effects on mesoscale systems are deserving of much study, since not only do these clouds play an important role in the climate-radiation budget, but they may also be important for the development of mesoscale frontal system circulations. Formation of a working group to evaluate and develop PBL models in the mesoscale context would be highly beneficial. We need to design field experiments that can simultaneously measure the PBL and the overlying convection using aircraft, acoustic sounders, wind profilers, lidars, and radars simultaneously. The use of chemical species as tracers in observing the transport properties of PBL turbulence and clouds was highly recommended. However, before the CME takes place, we need to gather information on what prior field experiments have and have not learned. Funds should be provided not only for carrying out field programs, but also for their design and for the analysis of their data.

It is vitally important to expand our basic knowledge of how MCSs influence climate through their extensive cloud shields and increase of humidity in the upper troposphere and to improve radiation parameterizations used in models. One of the most critical problems facing modelers presently is that no consistent radiation-microphysical coupling exists in current mesoscale radiative transfer schemes. It will be extremely helpful to develop and validate a community radiative transfer code suitable for use with mesoscale models, and to establish an intercomparison project to isolate and understand radiative processes in mesoscale models. Equally important is the need to improve our understanding of the influence of radiation and cloud microphysical properties on MCS dynamics. It should be a major scientific objective of CME to provide observations to establish the radiative budgets of different kinds of MCSs throughout their entire life cycle, and to present results from mesoscale models and field studies in their more global climate context.

Evapotranspiration modeling presents the most serious challenge in coupled land surface/hydrology/atmospheric models, and soil-water content is the single most important land-surface variable in atmospheric prediction models. There is a critical need for time-series measurements of soil moisture profiles to complement other mesoscale data, particularly in the dryline-prone regions of the High Plains contained within the CME enhanced observational area. The CME presents opportunities to expand upon our present inadequate knowledge of mesoscale circulations forced by inhomogeneous land surface characteristics, and to develop approaches for parameterizing their effects in mesoscale and larger-scale models. It was recommended that high-resolution OSSEs should be conducted to examine sensitivity of the atmosphere to the quality, distribution, and sampling of various land surface and vegetation parameters prior to CME. There is a

need to permit two-way interactions between atmospheric, biophysical, hydrological, and chemical processes. This feedback is essential in order to properly represent the control on transpiration of water into the boundary layer environment and the dry deposition of chemical species. These interactions point to the necessity for interdisciplinary activities in the CME involving the hydrology, ecology, and chemistry communities.

The current knowledge and research needs for chemistry on the meso and cloud scales was also reviewed. It was discussed how tropospheric ozone is a multiscale problem and how uncertainties that exist in many regional and cloud-scale chemical models could be reduced by incorporating chemical measurements and modeling into the CME. Conversely, the use of chemical tracers in a CME can help define air motions on both cloud and mesoscale. Photochemical models which are run in conjunction with cloud models are limited by a lack of observational data to verify convective transport of ozone precursor gases and subsequent ozone production. Also needed is vastly improved information on the role of cloud microphysical processes in chemical scavenging and the role of lightning in NO formation. Profiles of chemical trace species should be measured simultaneously with those of temperature, humidity, and winds. Chemical measurements can provide a valuable set of observations that can be used to assess the performance of cumulus parameterization schemes and to determine the overall transport due to an ensemble of nonprecipitating cumuli.

Although nonhydrostatic coupled cloud/mesoscale models have recently demonstrated the ability to predict MCSs, squall lines, hurricane rainbands, mesoscale gravity waves, and mesoscale frontal structures embedded within an extratropical cyclone, very limited quantitative verification of the models has been performed. As a result, the accuracy, the systematic biases, and the useful forecast limits have not been properly defined for these models. The key element in verifying mesoscale forecasts is the availability of mesoscale observations. Broad rawinsonde coverage at a variety of scales is needed if we are to capture the genesis, development and dissipation stages of the MCS. This is essential if we are going to advance cloud/mesoscale models for predicting the initiation and organization of mesoscale convective systems. High resolution, high quality moisture measurements (including precipitation) are required to validate model hydrological processes. Comprehensive dual Doppler radar coverage is required to validate couple meso/cloudscale model simulations of MCS circulations. It was felt that the CASH program could be a critical element of CME, provided that it was in place by the time of the field experiment. Cloud water/ice were identified as important missing parameters in conventional observations, not only with respect to model initialization, but also for radiation budgets. Although various assimilation schemes might provide decent estimates of this variable, it might be the Achilles heel of the modeling effort, particularly with regard to the upper levels, where stratiform clouds play such a major role in radiative processes. The scientific steering committee for CME should also consider collaborating with the COMPARE project by providing a set of scientific hypotheses to be verified by coordinated numerical experimentation using data and analyses drawn from a CME event.

Other principal unknowns concern telecommunications, computing facilities, and data storage and display strategies. It will be necessary to assess the need for upgraded telecommunications capabilities. It is essential to identify a "state-of-the-art" model to be used for both real-time forecast assistance in the field operations, as well as for assimilating the observations and to evaluate the model's predictive capabilitie for CME. The use of adaptive grids was strongly endorsed in the realtime prediction support, though the role of adaptive grids in creating the assimilated datasets for post-analysis is not so strongly advocated. CME should encourage groups to re-evaluate the state-of-the-art in adaptive refinement at various times prior to the field experiment.

Finally, it would be wise to emphasize linkages between CME and climate, not only to assess the impact of CME data on medium-range prediction, but also to validate parameterizations used in global models, and to make assessments regarding the impact of orphan MCS cloud residue on medium- and long-term predictions and climate change. The CME could uniquely provide information on moisture transports from the tropics to mid-latitudes, with emphasis on global responses.

1. Introduction

Approximately 40 scientists and program managers from the U. S. Weather Research Program (USWRP, a.k.a. STORM), the Global Energy and Water EXperiment (GEWEX) Continental-scale International Project (GCIP), the GEWEX Cloud Systems Study (GCSS), the GEWEX Water Vapor Project (GVaP), the Atmospheric Radiation Experiment (ARM), and the Aviation Weather Program (AWP) gathered in Ft. Collins, Colorado on 29-30 April 1992 to discuss the possibility of collaborating in order to develop a Cooperative Multi-scale Experiment (CME), whose central focus would be multiscale studies of Mesoscale Convective Systems (MCSs). It was agreed that CME should be considered a long term effort with one of the major components being a field experiment in 1995. The group suggested that the scientific objectives of the CME should include increasing the understanding of: (1) how scale-interactive processes generate and maintain MCSs; (2) the relative roles of balanced and unbalanced circulations in MCS dynamics; (3) the predictability of MCSs; (4) the role of MCSs in large-scale atmospheric circulations and the relationship of MCS occurrence to variations in large-scale flow; (5) what data bases are required to initialize and validate coupled cloud-resolving/mesoscale models, that may be further coupled with hydrological or chemical models; and (6) the optimal use of four-dimensional data assimilation to retrieve cloud and state parameters from remote sensing instrumentation.

The Colloquium and Workshop on Multiscale Coupled Modeling, held at the Holiday Inn in Calverton, MD from 22-25 February 1993, was organized by Dr. Steven Koch, with assistance from Drs. William Cotton, Mitch Moncrieff, Kelvin Droegemeier, and others, to bring together a diverse group of modelers, program managers, and other scientists to address modeling issues of importance to planning for the CME. The primary purpose of the colloquium was to assess the current ability of numerical models to accurately simulate the development and evolution of mesoscale cloud and precipitation systems and their cycling of water substance, energy, and trace species. The primary purpose of the workshop was to make specific recommendations for the improvement of mesoscale atmospheric models prior to the CME, their coupling with cloud, cumulus ensemble, hydrology, and/or air chemistry models, and the observational requirements to initialize and verify these models. This is needed, since for this kind of cooperative program to be successful, it must contain a strong interdisciplinary and multiscale modeling component that is readily transportable to other regions of the world. It was also the intention of the organizers of this meeting to use the discussions and recommendations of the participants to help further establish the scientific basis of the CME.

Representatives from the national and international meteorological programs mentioned above, each of whom expressed a potential interest in collaborating together to achieve the unified purposes of the CME, discussed their respective programs at the start of the colloquium. During the three-day colloquium, keynote talks which reviewed the current status of modeling abilities and/or approaches in 11 various topical areas were given, along with other presentations and discussion of the issues. Working group sessions for each of these general topic areas occurred on the last day so that smaller groups could develop viable strategies for further development of coupled multiscale models and then make suggestions for observational requirements to initialize and validate such models. The working group discussions and writing were led by the keynote speakers, who afterwards presented their group's recommendations to the general plenary group for final discussion. The ultimate product of these proceedings is this report, which summarizes the current status of coupled multiscale model predictive abilities and the sub-grid scale physical parameterization, data assimilation, and computer/numerical approaches used in such models (or subclasses of such models). This report also contains the prioritized recommendations for model development and required observations made by the conference participants for use in planning for the Cooperative Multi-Scale Experiment program.

Section 2 describes the objectives of the various programs and their interrelationships as discussed by the program representatives. The proceedings from the colloquium are presented in Section 3 in the same order as the presentations were given. The proceedings and recommendations of the workshop appear in Section 4. The first name appearing under each colloquium session is that of the keynote speaker, who presented a review talk on the subject matter in his/her session. The names following that of the keynote speaker in each session are the others who presented formal talks. Most of these talks were likewise of a review nature, rather than merely being presentations of the author's latest research accomplishments such as are typically presented at a scientific conference. A condensed summary of the issues and recommendations resulting from all the presentations and discussions is given in Section 5. The list of the participants who attended the colloquium and workshop appears in Appendix A.

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2. Scientific program descriptions

2.1 United States Weather Research Program (USWRP)

Chandrakant Bhumralkar

After more than a decade of development by a broad cross-section of the U. S. atmospheric research community involved in planning for the National STORM Program, the Subcommittee on Atmospheric Research (SAR) of the Committee on Earth and Environmental Sciences (CEES) led the development of a strategic plan to realize the objectives of STORM so as to improve our nation's capability to provide accurate short-term forecasts of weather. This strategic plan will guide the planning and implementation of what is now called the United States Weather Research Program (USWRP), which was approved by the President's Office of Science and Technology Policy in 1992. Recently, the USWRP Program Office responsibilities were shifted from the NOAA Office of the Chief Scientist to the Office of Oceanic and Atmospheric Research in NOAA. The current activities include completion of: the science and implementation plan, the post-field phase activities of the STORM-FEST experiment (the first multiscale field experiment conducted under the auspices of the USWRP, held in early 1992), and the data management system.

The USWRP is charged with achieving operational atmospheric prediction based on mesoscale observations and model results, and establishing the scientific and technological basis for global atmospheric mesoscale prediction by the year 2000. Key scientific questions being addressed under USWRP are:

- What is the role of scale interactions in determining mesoscale weather system structure, movement, and evolution?
- What are the feedbacks of these interactions and processes to weather on the large scale?
- What processes determine the timing, location, amount, and type of precipitation?
- How do mesoscale weather events impact hydrology?
- What are the limits of mesoscale predictability?

The modernization of the National Weather Service observing systems to include a network of 30 wind profilers in the central U. S., over 1000 Automated Surface Observing System (ASOS) stations, essentially complete coverage of the nation with a broad network of NEXRAD (WSR-88D) Doppler radars , and the GOES-Next satellite suite with its improved

profiling and imaging capability, will form the foundation for a range of systems tests and mesoscale research field experiments never before possible. The USWRP places high priority on developing science plans and defining specific implementation activities for: (a) fundamental research, (b) forecast applications, (c) predictive modeling, (d) data collection, analyses, and management, and (e) education and training. While there has been some early attention to item (d) with regard to the proposed multiscale field experiment, the USWRP will work with the scientific community to address the larger issue of *multiscale experiments versus smaller efforts focussed on regional forecast problems, as vividly demonstrated in the recent outbreaks of severe weather over the southeastern U. S.* Specific field experiments and other acitvities will be developed by the USWRP Scientific Advisory Committee (SAC) working in conjunction with the mesoscale research community, and approved by the SAR interagency working group. Field experiments of the CME-type will depend crucially on the following factors:

- Successful budget initiatives in FY95 and beyond by NOAA and the other SAR agencies
- The modernization deployment schedules for the new observing systems
- Linkage and optimization of field systems with those of other related programs, such as ARM, GEWEX, and AWP.

There are common objectives and database requirements between the USWRP and other programs (as discussed below), so *non-competitive synergism between the various programs must be established.* It is also incumbent upon the mesoscale modelling community to closely examine their observing system requirements for future field experiments. We must perform OSSE-type experiments to see if the large number of special balloon-borne soundings required in previous field programs such as STORM-FEST, *a major cost driver,* can be relaxed by incorporating the higher spatial and temporal resolution inherent in the new operational observing systems like NEXRAD, wind profilers (some with RASS sounders), and ASOS.

N94-24376

2.2 GEWEX Continental-scale International Project (GCIP)

Paul Try

The Global Energy and Water Cycle Experiment (GEWEX) represents the World Climate Research Program activities on clouds, radiation, and land-surface processes. The goal of the program is to reproduce and predict, by means of suitable models, the variations of the global hydrological regime and its impact on atmospheric and oceanic dynamics.

However, GEWEX is also concerned with variations in *regional* hydrological processes and water resources and their response to changes in the environment such as increasing greenhouse gases. In fact, GEWEX contains a major new international project called the GEWEX Continental-scale International Project (GCIP), which is designed to bridge the gap between the small scales represented by hydrological models and those scales that are practical for predicting the regional impacts of climate change. The development and use of coupled mesoscale-hydrological models for this purpose is a high priority in GCIP. The objectives of GCIP are to:

- Determine the time/space variability of the hydrologic and energy budgets over a continental scale region.
- Develop and validate macroscale hydrological models, related high resolution atmospheric models, and coupled hydrologic/atmospheric models.
- Develop and validate information retrieval schemes incorporating existing and future satellite observations coupled with enhanced ground-based observations.
- Provide a capability to translate the effects of a future climate change into impacts on water resources and temperature on a regional basis.

GCIP would benefit from a cooperative multiscale experiment by providing data: (1) for helping to provide closure on the water and energy budgets without the need for reliance upon residuals from conventional rawinsonde observations; (2) for initializing and verifying high resolution atmospheric models, land surface, and convective parameterization schemes; and (3) as input into hydrological calculations and models. The basic premise for GCIP is that, to the extent possible in developing coupled hydrologic-atmospheric models, it will rely upon operational or planned special observing programs in the Mississippi River basin region, assemble the relevant data sets, and develop a data management system to support the program. Of particular importance are high-resolution data products consisting of precipitation derived from the WSR-88D radars and satellites, winds from the profiler network, and temperature and water vapor profiles from rawinsondes, aircraft, and satellites.

The data collection part of the GCIP Implementation Plan is now in final draft form, although the research program and data management volumes await completion. The Science Plan has been available for some time, and the hydrology activities are now progressing with the establishment of a hydrology subpanel. Plans for providing GCIP Initial Data Sets (GIDS) on CD-ROMs prior to the beginning of the Enhanced Observing Period (EOP) in 1995 are being finalized. GIDS will consist of the following components:

• GIDS-1: the GCIP Static Data System Test will make use of existing operational and experimental capabilities to provide data from the period 1 Feb-30 April 1992, which includes the STORM-FEST data period of 1 Feb-15 Mar 1992

• GIDS-2: an Initial Retrospective Data set consisting of operational data collected in 1987-88 for the purposes of conducting diagnostic and evaluation studies of current capabilities to compute energy and water budgets within or over the GCIP region, in concert with the Satellite Pathfinder studies

• GIDS-3: the GCIP Integrated Systems Test (GIST), scheduled for a three-month period sometime between 1 April and 30 September 1994 for the purpose of evaluating the capabilities of the existing observing networks, operational models, and data centers to support the GCIP initial diagnostic, evaluation, and modeling studies as a buildup for the GCIP EOP. This test will utilize existing operational data and any other auxiliary data which could be provided by other programs (e.g., ARM and the Oklahoma mesonetwork). The GIST region is shown in Fig. 1. GCIP is considering providing augmented observations in the form of some added soundings and surface energy budget stations for a 5-7 year period at some of the sites composing the profiler hexagonal array that surrounds the CART site, as discussed in section 2.5.

The Enhanced Observation Period of GCIP would benefit from augmentation of the nation's observing capabilities during the latter part of this decade, with an increase in radiosonde data, support for the development of the Commercial Aircraft Sensing of Humidity (CASH) program, and the possible establishment of several radiation flux tower systems across the central U.S., 915 MHz wind profiler systems, and ground-based DIAL (DIfferential Absorption Lidar) systems along the southern rim of the U.S. to measure the low-level inflow of moisture into the GCIP continental region from the Gulf of Mexico. These and other supporting measurement systems for GCIP are depicted in Fig. 2.

2.3 GEWEX Cloud Systems Study (GCSS)

N94-24377

Mitch Moncrieff

The GEWEX Cloud Systems Study (GCSS) program seeks to improve the physical understanding of sub-grid scale cloud processes and their representation in parameterization schemes. By improving the description and understanding of key cloud

system processes, GCSS aims to develop the necessary parameterizations in climate and numerical weather prediction (NWP) models. GCSS will address these issues mainly through the development and use of cloud-resolving or cumulus ensemble models to generate realizations of a set of archetypal cloud systems. The focus of GCSS is on mesoscale cloud systems, including precipitating convectively-driven cloud systems like MCSs and boundary layer clouds, rather than individual clouds, and on their large-scale effects. Some of the key scientific issues confronting GCSS that particularly relate to research activities in the central U. S. include the need to:

- Produce a global climatology of MCSs and understanding of the role of mesoscale convectively-driven circulations in the global circulation.
- Produce new flux parameterizations for organized convection and a suitable closure for organized and mesoscale fluxes in global models.
- Understand the effects of the ice phase and radiative fluxes on MCS transports.
- Understand the effects of mesoscale processes on the coverage of boundary layer clouds and how to parameterize these relationships.
- Develop a suitable parameterization of cloud water content, entrainment rates, cloud radiative properties, and the influence of cloud condensation spectra on stratocumulus cloud microphysical and radiative properties.

Observations from field programs will be used to develop the cloud resolving models which, in turn, will be used as test beds to develop the parameterization schemes for the large-scale models. The cloud-resolving models provide synthetic data sets representing rather complete descriptions of entire cloud systems from which it will also be possible to develop algorithms for remote sensing observations. GCSS ultimately aims to develop the scientific basis for cloud process parameterization. New data sets that can adequately measure scale interactive aspects for comparison with the cloud-resolving model simulations need to be identified.

There are mutually supporting elements between GCSS and several of the other programs discussed in this report, as shown in Fig. 3. For example, the specific data requirements defined by the GCSS Science Team include the need (common with the objectives of the USWRP) for obtaining information on the large-scale forcing and mesoscale dynamical processes, which plays a controlling role in the generation and evolution of many cloud systems. GCSS also requires accurate determination of the profiles of the apparent sources of heat, moisture, and momentum throughout the atmosphere, information which would also go far in satisfying the GCIP need to understand the sources of error which accrue from attempting to determine water and energy budgets at the

continental scale. These profiles are most accurately obtainable on scales sampled by Doppler radars and research aircraft. The distribution of cloud properties in the grid volume, including the radiative flux profile and microphysical properties associated with the clouds, is also a GCSS requirement, a need which can perhaps best be met by coordinating with the ARM and GVaP measurement programs. Finally, GCSS requires information on the distribution of internal cloud properties (e.g., updrafts and downdrafts, mass fluxes, and microphysics), for which very detailed measurements will be needed. Thus, for the planned GCSS study of the MCS type of cloud system, it is essential that a multiscale experiment be performed. The plan is to have the GCSS working groups finalize the Implementation Plan, which is in draft form, by early 1994. A summary of the GCSS strategy is published in the Science Team Report (Betts et al. 1993).

N94-24378

2.4 GEWEX Water Vapor Project (GVaP)

David Starr

The goal of the GEWEX Water Vapor Project (GVaP) is to improve the understanding of water vapor in meteorological, hydrological, and climatological processes through improving knowledge of water vapor and its variability on all scales. This goal clearly requires a multiscale observing strategy. A pilot project was deemed the most appropriate first step toward achieving this goal. An implementation plan has been developed for this pilot phase, which has four research components:

- The assessment of current capabilities to determine the global distribution of water vapor content using various spaceborne remote sensing instruments and algorithms through a rigorous comparison focused on the period July 1987-June 1989.
- Operation of a state-of-the-art, research quality, multisensor Water Vapor Reference Station at the ARM/CART site near Lamont, Oklahoma for a continuous period of 3 months in late spring of 1995 (which coordinates perfectly with the CME plans).
- Performance of a systematic, intensive intercomparison of as many of the available in situ and remote sensing water vapor sensors as possible during a 4-week episode within the 3 month operation period of the Water Vapor Reference Station.
- Initiation of research and development to define and fully characterize an optimum water vapor sensor and data processing system for use with operational radiosondes and to work toward international standardization with the World Meteorological Organization.

The GVaP Strategic Research Plan and the Pilot Phase Implementation Plan have both been published (Starr and Melfi 1991, 1992). The plans for the Water Vapor Reference Station instrumentation consist of adding a Raman lidar and three-hourly radiosonde

observations to the suite of ARM systems described below during the three-month deployment at Lamont, Oklahoma, and to operate these systems in a semi-continuous fashion (3-5 days on, 2-3 days off). The systematic instrument intercomparison project would involve balloon-borne instruments (e.g., carbon hygristor, humicap, and other sensors), surface and/or aircraft remote sensing systems (Raman lidar, microwave radiometer, FT interferometer, DIAL, and infrared spectrometer), and in situ aircraft observations (Lyman-α absorption hygrometer, chilled mirror dew point hygrometer, cryogenic collection, etc.).

GVaP requires high temporal resolution water vapor and wind profile measurements to obtain information concerning the spatial mean and sub-grid scale variability within satellite footprints and global climate model grid boxes (roughly 100 km on a side). Furthermore, the Water Vapor Reference Station would be partly concerned with understanding the causes and effects of this variability, particularly in relation to cloud processes. There is obviously considerable benefit to be gained by having GVaP coordinate its observing systems at this site with the ARM, GCSS, USWRP, and GCIP programs, particularly during the intensive intercomparison episode.

N94-24379

2.5 Atmospheric Radiation Measurement (ARM)/CART site

Bill Pennell

The Department of Energy's Atmospheric Radiation Measurement (ARM) goals are: (1) to provide an experimental test bed for improving the treatment of radiative transfer in global climate models (GCMs) under all kinds of cloud cover, and (2) to improve the parameterization and modeling of cloud formation, maintenance, dissipation, and related processes in GCMs. The following scientific requirements are most critical to the ARM objectives:

- Quantitatively describe the spectral radiative energy balance profile under a wide range of meteorological conditions.
- Identify the processes controlling the radiation balance by direct and comprehensive comparison of field observations with detailed calculations of radiative fluxes and associated cloud and aerosol contributions.
- Develop a knowledge base necessary to improve parameterizations of radiative properties of the atmosphere for use in GCMs. This requires intensive measurements on a variety of temporal and physical scales such as in the proposed multiscale experiment. A major thrust is placed on the role of clouds, including their distribution and microphysical properties.

Central to the experimental design philosophy of ARM is the need to obtain measurements that can improve and test GCM parameterizations of clouds and their microphysical composition. As such, the design of the planned six permanent base sites surrounding a central facility is derived from the GCM grid element needs. The first of the selected permanent base sites is at Lamont, Oklahoma, and is termed the U.S. Cloud And Radiation Transport (CART) site. As shown in Fig. 4 and elsewhere (Fig. 1 and Figs. 6-10), the CART central facility is located at the center of the innermost part of the Demonstration Wind Profiler network, colocated with the GVaP reference site, and positioned within both the GCIP regional domain and the CME experimental area (discussed below). The CART site (Fig. 5) consists of: (1) a central facility which contains equipment for measuring the radiation field directly and surface and cloud properties that affect the radiances, as well as both a 915 MHz and a 50 MHz wind profiler with RASS for measuring winds and temperatures above the central facility; (2) a three-dimensional mapping network with 20 km radius consisting of surface layer heat and moisture flux profiling, radiometric, and other meteorological systems; and (3) an extended network of stations designed to provide radiometric and meteorological data, including temperature and humidity profiles obtained from interferometric, microwave, and sounding systems. All of these many systems are either already operational or are planned for deployment by the end of 1993. It is planned to make continuous measurements at the CART site for a period of ten years.

In addition to the regular measurements at the CART site, a series of intensive observational periods will be performed for several days to 2-3 weeks as well as participation in any cooperative field campaigns in the region. Participation in such campaigns would be for the purpose of addressing scientific/technical issues which cannot be addressed with the regular suite of CART instruments. For example, consider this important question: Is there sufficient information observed over a CART site or modeled on the scale of a GCM grid column to uniquely describe and predict the radiative and cloud properties on that scale? This question is particularly relevant to high-level cirrus clouds and stratiform-anvil cloud debris of MCSs. That is, these clouds can form in regions of ascent and active convection ~500-1000 km upstream of the CART site (or GCM grid column) and be advected horizontally in the high winds aloft over the grid column or CART site. MCSs can form in regions favorable for deep convection, and owing to their inertial stability and associated long lifetimes, propagate 1000 km downstream, producing precipitation, diabatic heating, thick cloud layers, and hydrometeor distributions which control the radiative properties over the CART site, where conditions are not locally favorable for deep convection.

Observations beyond the CART site such as in the proposed multiscale experiment are needed to address these issues.

2.6 Aviation Weather Program (AWP)

N94-24380

Brant Foote

The Aviation Weather Program (AWP) combines additional weather observations, improved forecast technology, and more efficient distribution of information to pilots, controllers, and automated systems to improve the weather information provided to the air traffic control system, pilots, and other users of aviation weather information (e.g., dispatchers and airport operators). Specific objectives include the needs to:

- Improve airport and en-route capacity by accurate, high resolution, timely forecasts of changing weather conditions affecting airport and en-route operations (e.g., ceilings and visibility).
- Improve analyses and forecasts of upper-level winds for efficient flight planning and traffic management.
- Increase flight safety through improved aviation weather hazard forecasting (e.g., icing, turbulence, severe storms, microbursts, or strong winds).

The AWP would benefit from participation in a cooperative multiscale experiment by obtaining data for: evaluation of aviation weather forecast products (e.g., ceilings aud visibility, thunderstorm occurrences, and weather hazards), analysis or four dimensional data assimilation schemes, and experimental techniques for retrieving aerosol and other visibility parameters. A multiscale experiment would also be helpful to AWP by making it possible to evaluate the added benefit of enhanced data sets collected during the experiment on those forecast and analysis products. The goals of the CME are an essential step in attaining the long-term AWP objective of providing two-to-four hour location-specific forecasts of significant weather. Although the possibility of a funding role for the AWP in the Cooperative Multiscale Experiment is presently unclear, modest involvement of Federal Aviation Administration (FAA)/AWP personnel (particularly FAA-supported modeling work) could be expected.

N94-24381

2.7 Scientific goals of the Cooperative Multiscale Experiment (CME)

William Cotton

Mesoscale Convective Systems form the focus of CME. Recent developments in global climate models, the urgent need to improve the representation of the physics of convection, radiation, the boundary layer, and orography, and the surge of interest in coupling hydrologic, chemistry, and atmospheric models of various scales, have emphasized the need for a broad interdisciplinary and multi-scale approach to understanding and predicting MCSs and their interactions with processes at other scales. The role of mesoscale systems in the large-scale atmospheric circulation, the representation of organized convection and other mesoscale flux sources in terms of bulk properties, and the mutually consistent treatment of water vapor, clouds, radiation, and precipitation, are all key scientific issues concerning which CME will seek to increase understanding. The manner in which convective, mesoscale, and larger scale processes interact to produce and organize MCSs, the moisture cycling properties of MCSs, and the use of coupled cloud/mesoscale models to better understand these processes, are also major objectives of CME. Particular emphasis will be placed on the multi-scale role of MCSs in the hydrological cycle and in the production and transport of chemical trace constituents. The scientific goals of the CME consist of the following:

- Understand how the large and small scales of motion influence the location, structure, intensity, and life cycles of MCSs.
- Understand processes and conditions that determine the relative roles of balanced (slow manifold) and unbalanced (fast manifold) circulations in the dynamics of MCSs throughout their life cycles.
- Assess the predictability of MCSs and improve the quantitative forecasting of precipitation and severe weather events.
- Quantify the upscale feedback of MCSs to the large-scale environment and determine interrelationships between MCS occurrence and variations in the large-scale flow and surface forcing.
- Provide a data base for initialization and verification of coupled regional, mesoscale/hydrologic, mesoscale/chemistry, and prototype mesoscale/cloud-resolving models for prediction of severe weather, ceilings, and visibility.
- Provide a data base for initialization and validation of cloud-resolving models, and for assisting in the fabrication, calibration, and testing of cloud and MCS parameterization schemes.
- Provide a data base for validation of four dimensional data assimilation schemes and algorithms for retrieving cloud and state parameters from remote sensing instrumentation

The importance of studying the scale-interactive processes that govern the frequency, location, evolution, and feedback effects of MCSs is clear in light of the role that they play in producing severe weather and their impact upon the earth's global-scale circulation, climate, hydrological cycle, and chemical and electrical balances (through their vertical and horizontal transports of water substance, heat, momentum, and chemical trace species, and because of their radiative and electrification effects). A multiscale experiment is required because MCSs range in scale from 100 to 400 km, yet they alter the atmosphere on scales of 1000's of kilometers, and they are composed of thunderstorm elements on scales of <10 km which produce a significant fraction of the fluxes, heating, rainfall, and severe weather. Furthermore, since MCSs have lifetimes of the order of 10 hours or more, to capture their entire lifecycle requires a network of the order of 3-4 $\times 10^3$ km in scale. Finally, the genesis of MCSs is thought to be the result of processes occurring over a wide range of scales, from that of jet streaks (L ~2500 km) to that of mesoscale instabilities and surface physiographic variations (L ~10's to 100's of kilometers). Moreover, such a multiscale experiment is necessary to initialize and validate regional and mesoscale models and to assist in the development and testing of MCS parameterization schemes for use in global-scale models.

The CME scientific steering committee has chosen the central United States as the location for study of mesoscale convective systems. Although from a climatic and hydrological point of view, the greatest impact of mesoscale convective systems is at tropical latitudes, especially over the oceans, these regions are not data-rich. Furthermore, expensive, logistically difficult experiments such as TOGA COARE, which provide only snapshot coverage of MCSs and very spotty larger scale meteorological coverage as well, are required in such regions. Fortunately, there is also a high frequency of MCS activity over the central United States in the spring and summer months, and research has shown that many of these mid-latitude systems are similar to their tropical cousins. Thus, models and cloud parameterization schemes developed and tested with high density data in the mid-latitude environment (which ranges from highly baroclinic to nearly tropical) can be more easily tested, modified, and adapted to the tropical environment with sparse data. Of course, the biggest advantage of performing a multiscale experiment in this region is the availability of frequent, high density operational measurement systems ranging from standard rawinsonde soundings, to automated surface stations, a network of wind profilers, modern WSR-88D doppler radars, and ACARS wind data. Thus an opportunity exists to carry out a true multiscale experiment by supplementing these standard observational systems with special research-grade systems at relatively modest cost. Furthermore, the ARM program provides an additional source of regular radiation measurements plus supplemental wind profiler and surface measurements that further reduces the cost of

carrying out a multiscale experiment. Finally, as already discussed, the other programs which have an expressed interest in cooperating in a multiscale experiment to study MCSs (USWRP, GCIP, GCSS, GVaP, ARM, and AWP) all have plans to concentrate their separate activities within this region.

A cooperative experiment is needed, because even though the costs of implementing a multiscale experiment in the central U.S. is reduced by the availability of routine measurement systems, the total additional observing systems needed to provide the necessary multiscale measurements is still quite expensive. The other programs (decribed above) share a common interest in furthering our understanding of MCSs and would benefit from a major multiscale experiment, yet no single one of these programs is likely to muster the resources needed to carry this out. A cooperative program is the wisest investment of resources if multiscale, interdisciplinary processes are the focus, so it is important that these programs join forces to implement such a multiscale experiment.

The multi-scale experiment is proposed to consist of meso-α scale arrays (Figs 6 and 9), meso-β scale arrays (Figs. 6, 7, 8, and 10), a meso-γ scale array (likely located at or near the CART/ARM site or within the Chickasha Watershed study area (Fig. 4)), and mobile platforms like aircraft. Ideally, running the field experiment from mid-April to mid-August in 1995 would allow sampling both spring storms residing in a rather baroclinic environment and mid-summer storms which reside in a more barotropic, tropical-like environment. Three plans are presently being considered, in order of decreasing breadth and cost: (a) a four-month field program, which would cost \$5-6M in new monies; (b) two 6-week programs designed to sample the broad range of MCSs while realizing an added risk of sampling few storms of a given type, which would cost \$4M; and (c) a single 2-month program running from about 20 May to 7 July, which is a further compromise in design in order to reduce the direct costs of running the experiment to its minimum (\$2M). Details appear in the CME Draft Science Plan.

The overall organization of the CME consists of a scientific steering committee, an experiment implementation committee, a project management committee, and a science team. The scientific steering committee should consist of leading scientists participating in the various component programs who can provide scientific leadership in the experiment design, implementation, operation, data archival, and procurement of facilities by serving as principal investigators on proposals and requests for facilities. An experiment implementation committee, to be formed by the scientific steering committee, will finalize details in the experiment design, determine field operational procedures, data management

procedures, and data archiving. A project management committee, to consist of one or more representatives from each of the cooperative programs and agencies, will be formed to provide direct interfaces with the cooperative programs and national and international agencies. A field project support office will provide logistical suport in carrying out the various recommendations provided by the working committees, including processing of documents, interfacing with program and agency representatives, organizing meetings, providing data management, and guidance and participation in field program implementation. Finally, a science team will consist essentially of all participating scientists in the cooperative field program.

3. Colloquium presentations

N94-24382

3.1 Grand challenge scientific questions in coupled modeling

Steven Koch

The "kickoff presentation" by the colloquium organizer was designed to set the background for the colloquium. Differences between past convective field experiments and the present opportunity for a truly multiscale field experiment were highlighted. This opportunity has arisen in part from the modernization of the nation's weather observing capabilities and also from the recent or planned establishment of special observing systems over the central U.S. by several new programs (ARM, GVaP, etc.). Most convective field experiments in the past (e.g., SESAME, CCOPE, CINDE) have attempted to resolve only the immediate scales of moist convection using network arrays that spanned two or three atmospheric scales at most. Furthermore, these scales have been defined more on practical considerations (cost, manpower, etc.) than on a clear understanding of their theoretical significance. Unfortunately, this has precluded a description of the entire life cycle of MCSs and their interaction with larger scale systems, the land surface, and trace species. Fortunately, the following factors now make it possible to attempt to simulate scale contraction processes from the synoptic scale down to the cloud scale, as well as interactions between complex meteorological, land surface, precipitation, chemical, and hydrologic processes with coupled, multiscale models:

- The availability of new technology to sample meteorological fields at high temporal and spatial resolution over a *broad* region made possible by the weather observing modernization program
- Increased computer power and improved numerical approaches to run limited area models with nonhydrostatic precipitation physics so as to explicitly resolve MCS processes
- Four dimensional assimilation of non-conventional data to provide dynamically consistent datasets for diagnostic analysis of nonlinear scale-interactive dynamics

Several examples of scale-interactive processes which present grand challenges for coupled, multiscale modeling were presented. For example, the comparative roles of dry dynamical processes relative to diabatic processes in causing the transition from strong symmetric stability to vanishing symmetric stability needs to be understood in order to assess the possible role of this process in organizing deep convection into bands, particularly in the presence of frontogenetical forcing. Another mesoscale instability process important to the MCS scale-interaction issue is associated with mesoscale gravity-inertia waves. A particularly well-documented example from CCOPE (the Cooperative Convective Precipitation Experiement) indicated that ageostrophic circulations associated with an unbalanced jet streak excited gravity waves that were instrumental in forcing the development of a strong summertime MCC in the Dakotas, and that the MCC subsequently appeared to produce local feedback effects upon the wave structure and energetics (Koch et al. 1988; Koch and Dorian 1988). However, the single-array sampling concept in CCOPE prohibited detailed study of the larger-scale behavior of the waves, their precise interaction with convection beyond the network, and the possible effects of the convection on the larger-scale flow. Another example of strongly scale-interactive processes includes cold fronts whose leading edge sometimes appears as a density current or internal bore capable of initiating frontal squall lines. These structures originate in some instances from cross-frontal radiative inhomogeneities caused by the cloud distribution across the front (Koch 1984; Dorian et al. 1988), in other cases from microphysical effects related to melting and evaporation (Parsons et al. 1987), and in still others to the interaction of mountains with tropopause folds (Koch and Kocin 1991). Clearly, a carefully designed multiscale experiment is required to fully understand and be able to correctly model these processes. Equally important and complex issues concern the interactions between boundary layer, surface, and topographic effects. Included in this list are interactions between sub-grid scale heterogeneity of land surface/vegetation and sub-resolvable fields of cumulus clouds, and the importance of interactions between boundary layer circulations and internal gravity waves in the overlying statically stable layer in organizing convective cloud systems. Finally, the possible influence of MCS momentum and heat transports and sources/sinks on larger scales of motion is poorly understood in terms of the following questions: (a) Are the feedback effects transitory or long-lasting and how deep of a layer is affected with what kind of dynamic balance? (b) How do these influences depend upon the character of the convective system, its life cycle, its interaction with the wind shear, etc.?

This keynote talk concluded with examples of important issues in each of the topic areas addressed in this colloquium: data assimilation, the measurement and modeling of

moist processes, the parameterization of sub-grid scale convection, coupled land surface/hydrology/mesoscale models, coupled chemistry/atmospheric models, boundary layer and radiative transfer processes, the validation of coupled multiscale models, and techniques and resources for storm-scale numerical weather prediction. Since many of these ideas appear as recommendations from the workshop (see section 4), they are not recorded here.

N94-24383

3.2 Next generation initialization techniques

Tom Warner: Overview of the Mesoscale Data-Assimilation Problem

John Derber:	*An overview of variational data assimilation techniques, and practical approximations for operational implementation*
Milija Zupanski:	*Current status and plans for regional four-dimensional variational data assimilation research at NMC*
Steve Cohn:	*Some fundamental problems in data assimilation*
Hans Verlinde:	*Overview of the state of the art for initialization of cloud models*

Four-dimensional data assimilation strategies can generally be classified as either current or next generation, depending upon whether they are used operationally or not. *Current-generation* data-assimilation techniques are those that are presently used routinely in operational-forecasting or research applications. They can be classified into the following categories: intermittent assimilation, Newtonian relaxation, and physical initialization. It should be noted that these techniques are the subject of continued research, and their improvement will parallel the development of next generation techniques described by the other speakers in this session. *Next generation* assimilation techniques are those that are under development but are not yet used operationally. Most of these procedures are derived from control theory or variational methods and primarily represent continuous assimilation approaches, in which the data and model dynamics are "fitted" to each other in an optimal way. Another "next generation" category is the initialization of convective-scale models, a topic which was reviewed by Hans Verlinde.

Intermittent assimilation systems use an objective analysis to combine all observations within a time window that is centered on the analysis time. The background or first-guess field is obtained from a model forecast that is valid at the analysis time. The model is then integrated forward for a short period of time, and the analysis step is repeated. Through this sequence of analyses and short forecasts, a four-dimensional data set is produced. *Continuous first-generation assimilation systems* are usually based on the Newtonian-relaxation or "nudging" techniques. Here the observations are inserted at each time step

during a preforecast model integration cycle. In this procedure, the model simulation can be relaxed toward observations, objective analyses of the observations, or both observations and objective analyses simultaneously. *Physical initialization procedures* generally involve the use of standard or nonstandard data to force some physical process in the model during an assimilation period. An example is the use of precipitation-rate data to infer latent-heating rates which can be substituted for the model-defined rates during the assimilation period. Other hydrologic information such as cloud distribution and surface moisture can be utilized to specify model-predicted variables during the assimilation period.

Under the topic of next-generation assimilation techniques, variational approaches are currently being actively developed. *Variational approaches* seek to minimize a cost or penalty function which measures a model's fit to observations, background fields and other imposed constraints. Minimization of the cost function will, in principle, yield the initial conditions that produce the best forecast from that model. In the "adjoint" approach, the adjoint of the numerical model is integrated backward over the data assimilation period (after a forward integration of the forecast model), during which the observations are introduced. This allows the computation of the gradient of the cost function which is required to compute a minimum. The process is iterated until "suitable" convergence to the optimal initial conditions is obtained. Alternatively, the *Kalman filter technique,* which is also under investigation as a data assimilation procedure for numerical weather prediction, can yield acceptable initial conditions for mesoscale models. A model error covariance term which is carried forward in time (thus allowing the minimization procedure to know the model error) is part of this assimilation system. The calculation of this term, however, is very expensive, and current research efforts are concentrating on how to reduce the computational cost while retaining the benefit of error covariance evolution.

The third kind of next-generation technique involves *strategies to initialize convective scale (non-hydrostatic) models.* This is required for a wide range of potential applications, ranging from the prediction of fog, visibility and ceilings, to the evolution of boundary layer phenomena such as plume dispersion and outflow boundaries, to the forecasting of severe thunderstorms. Since the primary observing tool for many of these applications will be Doppler radars, the key issue is the determination of initial conditions for all model variables from measurements of radial velocity and reflectivity in combination with other larger-scale data. It can be shown that simple insertion or nudging of wind data in a non-hydrostatic model will not recover the correct temperature field. However, modified forward insertion and dynamic relaxation techniques have shown some success if thermodynamic retrieval methods (or thermodynamic data) and/or other dynamical

constraints are incorporated Nudging or specification of moisture/water/ice parameters during assimilation is also being explored. Multi-parameter radar data are being exploited for use in the initialization of hydrometeors and other cloud microphysical parameters. These techniques usually assume the presence of a two- or three-dimensional wind field (say, from dual-Doppler analysis). If data from only one Doppler radar are available, then single-Doppler retrieval methods need to be applied. A wide variety of such methods exist to get two or three dimensional winds near the radar. Velocity azimuth display (VAD) and related methods just provide a vertical sounding of the horizontal wind for a volume around the radar. Tracking reflectivity echoes by correlation (TREC) deduces the horizontal wind field in a clean-air environment, primarily in the boundary layer. TREC winds have been combined with the thermodynamic retrieval technique to analyze and predict the movement of gust fronts. Other techniques, such as an adjoint advective retrieval have also done well in estimating boundary layer flows, in some cases using only reflectivity data. Finally, three dimensional winds as well as temperature and pressure have been estimated using radial velocity and reflectivity data in an adjoint dynamical retrieval method using a dry Boussinesq model. This technique has been demonstrated for a real-data gust front case but application to severe thunderstorm prediction awaits further progress in the adjoint formulation as well as in moisture initialization.

N94-24384

3.3 Examples of data assimilation in mesoscale models

Fred Carr: Overview of Physical Initialization Techniques

John Zack:	*The assimilation of asynoptic data into a mesobeta scale model*
Jerry Schmidt/ John Snook:	*The use of MAPS and LAPS to generate short-term (0-12 h) forecasts with the CSU-RAMS model*
Stan Benjamin:	*The Mesoscale Analysis and Prediction System- a 3h data assimilation system in isentropic-sigma coordinates*
David Stauffer:	*Dynamic initialization by Newtonian relaxation with the Penn State/NCAR mesoscale model*

Fred Carr gave the keynote address on the problem of physical initialization of mesoscale models. The classic purpose of physical or diabatic initialization is to reduce or eliminate the spin-up error caused by the lack, at the initial time, of the fully developed vertical circulations required to support regions of large rainfall rates. However, even if a model has no spin-up problem, imposition of observed moisture and heating rate information during assimilation can improve quantitative precipitation forecasts, especially early in the forecast. *The two key issues in physical initialization are the choice of assimilating technique and sources of hydrologic/hydrometeor data.*

One of the current techniques in use today includes the use of diabatic heating information in nonlinear normal mode initialization; the heating may either be from model estimates or from observed rainfall data (Fiorino and Warner 1981; Molinari 1982; Danard 1985; Ninomiya and Kurihara 1987; Wang and Warner 1988). A second technique in use is the direct specification of moisture and/or heating rates during a preforecast integration (dynamic initialization); this may or may not be accompanied by nudging of the primary variables. Finally, imposition of internal consistency among the observed precipitation and the model's initial temperature and moisture fields can be used; most often, the model's initial fields (sometimes including the divergent wind component) are modified in the process (e.g., Krishnamurti et al. 1988). *A major problem in all of the techniques is the need for accurate vertical distribution of the heating and moistening rates.*

Although suitable assimilation strategies will no doubt evolve, the data problem is more acute. Surface raingauge information represents a true source of mesoscale data but only a small fraction of it is available on an hourly, real-time basis. *Rawinsonde* data are of insufficient horizontal density while*ground- and space-based remote sensors* lack vertical resolution. Attempts have been made to overcome these problems by combining *infrared and microwave satellite estimates* with conventional surface and upper air observations to improve estimates of rainfall, precipitable water, and cloud and hydrometeor distributions (Kummerow et al. 1989; Manobianco et al. 1993). Detailed cloud water and ice data will be required to initialize meso-gamma scale models; these data will need to be deduced from the network of Doppler radars now being installed across the nation. The radar data will also be an excellent source of detailed precipitation estiamates. Since no single observing system will be complete, retrieval techniques will be needed to deduce unobserved quantities from variables that are observed.

John Zack presented a series of meso-beta scale model experiments with an 11 km version of the MASS model designed to investigate the sensitivity of convective initiation forced by thermally direct circulations resulting from differential surface heating to four dimensional assimilation of surface and radar data. During the morning hours of this case, an east to west cloud band was present over the northern portion of the Florida peninsula. An isolated area of convection developed in the clear air just to the south of the cloud band in the well-heated surface air at the intersection between a line of convergence forced by the sea breeze circulation and a line forced by a thermally direct circulation between the cloudy air to the north and the clear air to the south. The model run which assimilated surface temperature, dew point and wind information during the first three hours of the simulation developed a more realistic temperature gradient during the nudging period.

However, as soon as the nudging period was over, the temperature reverted back to the pattern produced by the control simulation, because the surface temperature forcing functions (e.g., the amount of solar radiation reaching the surface) had not been significantly changed. The new afternoon convection also failed to develop in this simulation. Assimilation of heating and moistening rates inferred from manually digitized radar (MDR) data during the same 3-hour period dramatically improved the forecast by lowering the short wave transmissivity in the cloud band, forcing a more realistic temperature gradient between the clear and cloudy air, and initiating an isolated area of convection within 50 km and 1 hour of its observed location. The experiments suggest that the assimilation of surface data may not be an effective way to improve short-term forecasts for cases in which gradients in surface energy budget forcing functions are the primary factor in determining the evolution of mesoscale low level circulations and convective initiation. In these cases it may be more effective to assimilate actual or even synthetic data (e.g. moistening rates inferred from MDR data) which can improve the representation of the forcing function. The results of these simulations underscore the need to accurately initialize and simulate grid and sub-grid scale clouds in meso- beta scale models.

Jerry Schmidt reported on the status of the application of the CSU-RAMS mesoscale model by the NOAA Forecast Systems Lab for producing real-time forecasts with 10-60 km mesh resolutions over $(4000\ km)^2$ domains for use by the aviation community. The model is currently run over four separate regions of the country on a sigma-z coordinate system with fully compressible nonhydrostatic physics and grid nesting (the value of Δx dependent upon the application). Either MAPS or LAPS model data are used to initialize the RAMS model on a 12-h cycle. The physical parameterizations currently used in the model include the Chen-Cotton radiation scheme, the Tremback-Kessler 11 layer soil model, deformation-dependent K closure, an upper absorbing layer, and a bulk ice/microphysics package, and a choice of cumulus parameterizations. An example application of the model to a Front Range blizzard case showed that the model successfully reproduced the observed mountain top westerlies, and the strong northwesterly flow residing on the eastern flank of a lee anticyclone, but only was able to capture the anticyclone with the LAPS-initialized run. A better representation of topography in the LAPS model may be one key to explaining these differences. Only a few wintertime cases have been run thus far, and it remains to be seen whether summertime flow conditions generate less favorable results. Future work will address the possible importance of the effects of low-level thermal boundaries, bands of mesoscale vertical motion, and other inhomogeneities in the initial state of the model.

Stan Benjamin discussed the use of the MAPS (Mesoscale Analysis and Prediction System) model. MAPS is the first mesoscale model to employ a 3h data assimilation in isentropic-sigma coordinates. He discussed the benefits realized by the use of isentropic coordinates, in particular the improvement in the analysis of upper-level frontal structures. The isentropic optimal interpolation procedure used in MAPS was also presented. Additional detail concerning MAPS sensitivity tests appears in Section 3.10.

David Stauffer first briefly discussed the demonstrated importance of data assimilation during the STORM-FEST project. Comparison of a control experiment using MAPS data for a static initialization with a dynamic initialization run performed on the 4 March 1992 case showed that the low-level rain water concentration agreed well with the composite radar imagery only when dynamic initialization was used, since the model's explicit moisture scheme was able to develop realistic fields of clouds and rainfall during the 12-h preforecast period while the larger-scale features were corrected via the analysis nudging. Other work at PSU has shown that more realistic precipitation forecasts result during the first few hours of simulation when the model is initialized with latent heating profiles inferred from radar-based rainfall rates and hourly raingage data. Research is currently underway to use 10-minute radar data on a 25-km nested grid to identify convection during the model assimilation cycle for the 10-11 June 1985 PRE-STORM squall-line case.

The focus of Stauffer's talk was on mesobeta-scale data assimilation using a triply-nested nonhydrostatic version of the MM5 model. Three meshes of 36-km, 12-km and 4-km resolution were used to model the meteorology in the San Joaquin Valley of California. Conventional 3-hourly surface and 12-hourly upper-air data are analyzed on the 36-km grid and interpolated to the 12-km grid. Analysis nudging is used to continuously assimilate these gridded data on both meshes by interpolating in time between successive analyses. In addition, special asynoptic data (rawinsondes, profilers, acoustic sounders, etc.) are assimilated over the 12-km and 4-km domains via an obs-nudging technique, in which the data directly influence a mesoscale region (based on topography and the height above ground) surrounding each observation during a prescribed time window. Local features such as the San Joaquin Valley nocturnal low-level jet and the Fresno eddy are realistically simulated by the model. Without data assimilation, the model- simulated diurnal surface temperatures agree well with observations, but afternoon mixing depths in the San Joaquin Valley are too high. When obs- nudging is used during the continuous assimilation period to assimilate 3- hourly multi-layer thermal data, mixing depths in the valley are more realistic; however, there are some interesting effects in the model wind field caused by the

nonuniform data distribution of the mass field. That is, anomalous circulations can develop at the edge of a data-dense region.

Finally, Stauffer discussed the use of the adjoint equations of a numerical model for internal parameter estimation. In an example using a 1-D shallow-fluid model, optimal control theory is applied to the determination of an "optimal" set of weighting coefficients used in the nudging approach, which relaxes the model state toward the observed state by adding to one or more of the prognostic equations artificial tendency terms which are proportional to the difference between the two states. The "proportionality constants" are usually based on scaling arguments, and modified by weighting functions which reflect the time and space separation of the model solution from the data, as well as data quality and representativeness. He demonstrated that the magnitude and distribution of these coefficients can be determined using the shallow-fluid model and its adjoint such that the model error during the assimilation period is optimally reduced subject to some constraints.

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3.4 Measurement and modeling of moist processes

William Cotton: Explicit Simulation of Mesoscale Convective Systems

David Starr:	*Measurement of water vapor and other constituents of the hydrologic cycle*
Kenneth Mitchell:	*NMC plans for initializing soil hydrology for mesoscale models*
Rex Fleming:	*Water vapor measurement concepts for GCIP*
Steve Koch:	*Mesoscale moisture analysis using satellite data*
Steve Smith:	*Mesoscale wind analysis using satellite data*
Jocelyn Mailhot:	*Recent activities in modeling of moist processes in mesoscale systems*
Don Perkey:	*Effects of temporal resolution on heat and moisture budgets for cumulus parameterization*
Greg Tripoli:	*Modeling scale interaction processes*

The keynote talk given by William Cotton summarized five years of his work simulating observed mesoscale convective systems with the RAMS (Regional Atmospheric Modeling System) model. *Excellent results are obtained when simulating squall line or other convective systems that are strongly forced by fronts or other lifting mechanisms.* Although the overall existence of convection was reproduced, the Doppler-observed mesoscale circulations could not be reproduced, even when exploiting alternate analysis software and using grids with sufficient resolution (Δx = 2.2 km) to explicitly resolve cloud-scale motions. *Less highly forced systems are difficult to model* (e.g., the 3-4 June and 23-24 June 1985 PRE-STORM MCCs (Fig. 11)). It was surmised that in such weakly sheared, nearly barotropic environments, accurate predictions of MCSs may require: (a) details about the surface forcing (e.g., soil moisture and vegetation, outflow boundaries and gravity waves

triggered by earlier convection); (b) either improved cumulus parameterization schemes or explicit simulation of deep convection over domains as large as $(1000km)^2$ for a substantial part of the diurnal cycle; and (c) increased upper air sampling by rawinsondes and wind profilers to capture weak short-waves and jet streaks.

The discussion turned next to the measurement of water vapor. David Starr showed impressive accuracy measuring water vapor with both the airborne DIAL (Differential Aborption Lidar) system and the ground-based Raman lidar. The latter system can attain temporal sampling of 2 min and vertical resolution of 75 m to altitudes as high as 7 km at nightime, though with poorer resolution in the daytime. By contrast, the High resolution Interferometer Sounder (HIS) instrument resolves structure comparatively less well than the Raman lidar when operated from the ground, though its performance improves greatly when operated in a downlooking mode from the NASA ER2 platform, which flies at 20 km altitude. The rawinsonde performs well up to -40C and even reveals useful structure up to the -50C level. It is important to appreciate that *cloudy conditions compromise the measurements of all the remote sensing systems with the exception of satellite microwave data.* Although the rawinsonde used in some countries is seriously affected by moistening of the temperature sensor, the VIZ and Vaisala sondes used here and in Europe possess thermistor wetting problems that tend to be of limited duration and are quite recognizable. Starr also showed intercomparisons of SSMI and TOVS satellite moisture retrievals with ECMWF and NMC analyses.

Kenneth Mitchell presented NMC's plans for initializing land water hydrology in mesoscale models. By the end of the decade, NMC plans to run a national mesoscale model at 4 km, but surface observations of moisture and vegetation on that scale are unlikely. As a consequence, NMC plans to develop the AGROMET model to run daily in order to predict surface moisture and maintain a surface hydrology. The AGROMET model will run separately from the atmospheric prediction models. NMC expects to have an 80 km/38-level model operational by summer 1993 and a 40 km model operational by summer 1994, in time for the planned CME.

Rex Fleming spoke next on plans for enhanced observations for GCIP. He described plans for putting moisture sensors on commercial aircraft in a program called CASH, which would complement the ACARS program. Fleming emphasized the need to define water and energy processes and enhance low-level moisture and wind observations, particularly in a ``picket fence'' along the southwestern coast of the Gulf of Mexico so as to provide adequate sampling of the inflow conditions for GCIP.

Steve Koch and Steve Smith spoke on the subject of using satellite data to provide mesoscale moisture and wind analyses. Koch demonstrated that cloud cover can make an enormous difference in mesoscale flow and temperature structure across fronts, causing temperature variations on the order of 5C. Use of a satellite cloud classification scheme to provide three-dimensional relative humidity fields in cloudy conditions (thus, a useful complement to the ground and satellite-based sensors described by Starr) was shown to significantly improve mesoscale model forecasts of thermal fields and frontal circulations. Smith discussed the current satellite ability to obtain representative winds from cloud motions over land. Stereo methods of calculation yield height accuracies of 0.5 km compared to cloud shadow techniques which have 1 km accuracy. The usefulness of these winds depends on the availability and representativeness of the cloud motions (i.e., not only the existence of clouds, but on their character).

Jocelyn Mailhot reported on modeling activities at the Canadian Atmospheric Environment Service (AES) using a hydrostatic, variable-resolution grid model. He presented the results of two case studies involving a squall line and a cyclone from CASP II. The results showed the model did well distinguishing heavy from stratiform precipitation and finding icing zones. Mailhot concluded that more work was needed to improve model validation.

Don Perkey spoke next on the spatial resolution effects of moisture budgets. He showed that background budgets were essential to getting the local budgets correct, since they act as a check on the integral properties of the local system. The assumption that liquid and solid water storage does not vary over the averaging period as is commonly made in larger-scale moisture budget calculations is highly questionable at the mesoscale. This factor must be considered when attempting to relate the net source of water vapor to the atmosphere to the time/space averaged vapor flux divergence. Furthermore, residuals computed from the gridscale transport processes (derived from rawinsonde data) require knowledge of the radiative heating profile to define the apparent heat and moisture sources from sub-gridscale processes. Since the observed precipitation by rain gauges and WSR-88D radars must be equal to the fallout of water generated in the column and transported into it (or stored from an earlier time), any discrepancies between the observed and diagnosed rainfall is a measure of the importance of water storage and transport processes (assuming that the integrated effects of ice microphysical processes and the net convergence of eddy fluxes is negligible). Storage effects can become substantial when stored water falls out as rain from dissipating convection in an MCS. Significant heat and moisture transports occur

at the mesoscale by convection, in particular the transport from the convective to the stratiform region is important during the early and mature phases of such systems.

Greg Tripoli reported on some of his modeling studies showing scale-interactive processes both within a convective weather system and between the system and larger scales. Tripoli then presented what he found to be the processes causing spiral rain bands in a tropical cyclone: these include the complex scale interactions between the cyclone circulation, deep gravity-inertia waves in the cirrus outflow, and density currents driven largely by ice microphysical processes. He then showed the processes modeled to form gravity-inertia waves within a strongly baroclinic weather system. The processes were depicted in part through three-dimensional animation using VIS5D.

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3.5 Parameterization of sub-grid scale convection

William Frank: Overview of the cumulus parameterization problem

John Molinari:	*Interactions between explicit and implicit processes in mesoscale models*
Jack Kain:	*Effects of model grid size on the cumulus parameterization problem*
Mitch Moncrieff:	*Parameterizing convective effects on momentum fields in mesoscale models*
Mohan Karyampudi:	*Differences between slantwise and vertical cumulus parameterization*
Georg Grell:	*Experiments with different closure hypotheses*
William Frank:	*Coupling cumulus parameterizations to boundary layer, stable cloud, and radiation schemes*

Rather than give the details of each of the talks presented in this session, a summary of the issues will be given here. The discussion first briefly overviews the cumulus parameterization problem. More complete reviews of this topic already appear in the literature (e.g., Frank and Cohen 1987; Molinari and Dudek 1992). Current approaches are next discussed. Third, the strengths and weaknesses of existing parameterizations are presented. Recommendations appear in the workshop summaries.

1) Overview of the parameterization problem

Cumulus convection and mesoscale convective systems (MCSs) have major effects upon the mass, moisture and momentum fields. However, in most numerical models some or all of these phenomena are subgrid-scale. Hence, their effects on the resolvable-scale circulation must be parameterized. It is necessary to parameterize the combined effects of cumulus convection and MCSs in models with grid sizes $\Delta x > 100$ km, whereas in mesoscale models, which typically use grids of 10-50 km, the mesoscale circulations can be

resolved explicitly, but the convection still must be parameterized. With very fine grid meshes ($\Delta x<2$ km), one can simulate convective drafts explicitly, and cumulus parameterization is usually not used (though there are still many subgrid-scale processes that need to be parameterized).

Ideally, a cumulus parameterization scheme would predict all significant convective processes with perfect accuracy in terms of the existing grid-scale variables. In practice it is not possible to represent all subgrid scales, so parameterizations must be designed to optimize predictions of the most important physical processes. *The relative importance of convective heat and moisture processes is scale-dependent.* For example, in climate models it is crucial that the parameterization predict the proper evolution of the moisture field due to the strong long-term effects of water vapor and clouds on the radiation budget. On smaller scales it becomes extremely important to predict the location and rate of convective latent heat release, as the evolution of mesoscale systems is highly dependent upon the diabatic heating.

Direct effects of convection on the momentum fields appear to be very important over a range of scales (Moncrieff 1992). These effects are more complex than simple estimates of momentum transport by cloud parcels (cumulus friction). Much of the momentum exchange occurs due to meso-beta-scale circulations. While these circulations may be explicitly resolved in higher resolution mesoscale models, their effects must be parameterized in climate models or other coarse resolution models.

Cumulus parameterizations can be thought of as performing three individual tasks: (1) they must diagnose the presence of convection and activate the scheme (the so-called trigger function); (2) they must determine the properties of the convection and its effects on the grid-scale fields (a cloud model of some type is usually, though not always, used); and (3) they must estimate the amount of convection that occurs during the current time step (the closure). Not all schemes separate these functions, and if they are difficult to isolate, it is not easy to evaluate the effects of individual assumptions on the performance of the scheme as a whole.

2) Current Approaches

Cumulus parameterization is preferred to explicit resolution of moist processes as a method of simulating the effects of convection at scales above ~20 km. However, in models with grid meshes small enough to resolve moist mesoscale circulations (roughly 20-50 km),

it is desirable for a model to use both an explicit moisture scheme (to simulate the mesoscale circulations) and a cumulus parameterization scheme simultaneously, within the same grid column. The two schemes should interact realistically, including exchange of hydrometeors and air between clouds and the grid-scale circulation, an approach termed "hybrid parameterization" by Molinari and Dudek (1992). Most current cumulus parameterizations include assumptions of interactions between the cloud and the grid scale that become invalid when the convective clouds are not restricted to areas covering only a small fraction of the grid column. While there may be ways to reformulate the parameterizations (perhaps involving introduction of more parameters), *most current cumulus parameterizations do not appear to be valid when applied on grid meshes of less than about 20 km.* For grid meshes smaller than about 2 km, explicit moist processes appear to simulate the effects of convection better than do parameterizations. *However, when the grid mesh becomes greater than about 2 km, explicit moisture schemes tend to produce unrealistically large vertical drafts.* This raises the question of what to do when the optimum grid mesh for resolution of the phenomenon being studied lies between 2 - 20 km. Research is continuing to determine the best methods of simulating convection on this scale.

Most currently used cumulus parameterizations were designed for use in models with relatively coarse grids in which synoptic or larger scale circulations are simulated. In such models, there are sufficient temporal and spatial scale differences between the convection and the grid scale circulation that the convection can be assumed to respond to the evolving grid-scale circulation to maintain some sort of equilibrium. The grid-scale circulation is assumed to provide the forcing, and the convection responds either in a single time step or over a specified time interval to approach the hypothesized equilibrium state. Examples of convective equilibrium assumptions commonly used as closures in current schemes are:

- Moist convective adjustment assumes that convection forces the atmospheric lapse rates of temperature and moisture towards empirical profiles (Manabe et. al. 1969; Betts 1986).
- Rainfall is an empirical fraction of computed column-integrated moisture convergence (Kuo 1974).
- Clouds maintain the existing cloud-ensemble parcel instability, or quasi-equilibrium (Arakawa and Schubert 1974).
- Convective stabilization is sufficient to remove all or a fraction of the parcel instability within a specified advective time interval (Kain and Fritsch 1990).

Of these approaches, only the latter was designed for use on grid meshes as small as those typically used in mesoscale models (20-50 km), though all of the others have been tried on such scales.

3) Strengths and Weaknesses of Existing Parameterizations

There is a growing consensus within the parameterization community that moisture balance closures are too far removed from the physical processes that control convection to be used as the basis of a cumulus parameterization. Lapse rate adjustment schemes are simple, inexpensive and fairly stable and can be good choices for some modelling applications, but they are too empirical, and again too far removed from the processes that initiate and control convection, to be desirable for use in models with smaller grid meshes. The current trend is towards parameterizations in which the triggers and closures use concepts of parcel instability in some manner.

A major problem of parameterizing convection in models with grid spacings on the order of about 50 km or less is that the grid-scale circulation varies on approximately the same time scales as does the convection. Individual cumulus clouds typically have lifetimes of 15 - 60 minutes, sometimes longer. Since the individual grid columns are much smaller than the radius of deformation (L_R) in most instances, the heating released in the column causes a rapid adjustment of the mass field, dispersing the heating to very large scales (on the order of L_R). Unlike larger-scale models, which are usually predicting the evolution of large, relatively stable circulation features, the mesoscale model must often predict rapidly-varying, unbalanced circulations that are highly dependent upon the rate of local latent heat release.

The lack of temporal scale separation between convection and the grid-scale flow, as well as the small size of the grid column relative to L_R, have two major implications for cumulus parameterizations. First, to the extent that convection in heavily disturbed regions tends to approach a state of equilibrium with the large-scale fields, that equilibrium state is not predictable from the observed values within a local grid column. Rather the equilibrium requires knowledge of the fields and convection over a much larger area. Second, since convection varies on the same approximate time scale as the grid-scale circulation, it is not desirable to introduce a closure mechanism that estimates the amount of convection as that required to achieve equilibrium with the existing grid-scale conditions.

Despite the above inherent drawbacks in equilibrium-type closures, such closures may work reasonably well in models under the right circumstances (Grell et. al. 1991; Xu and Arakawa 1992). For example, if the convective scheme is activated at the right time in the right place, and if the rate of diabatic heating is equal to or slightly greater than the large-scale forcing (uplifting or other destabilization) in the column, then the heating will act to intensify the local circulation. If the parameterization scheme includes a realistic representation of downdrafts, these will eventually stabilize the column, shutting off the convection. Without downdrafts, the altitude of strongest diabatic heating will be so low as to cause erroneous positive feedbacks or "grid-point storms". It may not make too much difference whether the rate of heat release is accurate, so long as it is not less than the amount required to at least balance the grid-scale destabilization rate. Even if the heating rate is somewhat too large, it may tend to produce a similar amount of time-averaged heating in a column, over too short a time interval. On the other hand, if the scheme produces too little heating, the convection will not keep up with the grid-scale cooling, and the explicit moisture scheme will tend to produce explicit rainfall, which can greatly alter the characteristics of the solutions.

Another approach to closure in cumulus parameterization schemes is to predict the convection from processes that have strong controlling effects on the origins of the clouds, and then let the interactions between the cloud models and the grid-scale circulation determine their own equilibrium. Examples of this approach are Frank and Cohen (1987) and earlier schemes that use subcloud-layer mass convergence in some form for closure. These schemes do not assume any kind of equilibrium between the convection and the levels above cloud base. More recent approaches involve coupling cloud models to the turbulent fluxes in higher order turbulence models or to the mass flux predicted by boundary layer models. In each case, the amount and type of convection is predicted in terms of rapidly-varying local processes, and the evolution of the flow at higher levels reflects the interactions between the implicit convective fluxes and the grid-scale flow.

One problem with the rapid interactions between convective clouds and their organizing mesoscale circulations is that *there are no existing data sets with sufficient temporal and spatial resolution to verify closure hypotheses. Since the data cannot separate the convective response to grid-scale changes from the grid-scale response to convection, one can't tell whether equilibrium closures are working or not.* Verification of the schemes currently requires fully prognostic tests in which many other factors other than the cumulus parameterizations affect the outcome. It is highly desirable to obtain

measurements that would be adequate to verify at least some of the major assumptions of cumulus parameterizations directly from observations.

On the subject of verification, one problem with direct comparisons between the performances of different schemes in models is that each parameterization tends to be a complex package with a large number of components and assumptions. Further, the method of interaction between the scheme and the host model may cause different schemes to work better in different models strictly for numerical or procedural reasons. When testing cumulus parameterization assumptions using numerical simulations, it is highly desirable to use a simple, common parameterization system that allows isolation and testing of one assumption at a time, as demonstrated in Grell et. al. (1991).

3.6 Coupled land surface/hydrologic/atmospheric models

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Roger Pielke

Lou Steyaert:	*Prototype land cover characteristics data base for the conterminous United States*
Ray Arritt:	*Surface evapotranspiration effects on cumulus convection and implications for mesoscale models*
Mercedes Lahtakia:	*The use of a complex treatment of surface hydrology and thermodynamics within a mesoscale model and some related issues*
Chris Smith:	*Initialization of soil-water content for regional-scale atmospheric prediction models*
Conrad Ziegler	*Impact of surface properties on dryline and MCS evolution*
Su Tzai Soong	*A numerical simulation of heavy precipitation over the complex topography of California by*
Roni Avissar:	*Representing mesoscale fluxes induced by landscape discontinuities in global climate models*
Peter Wetzel:	*Emphasizing the role of subgrid-scale heterogeneity in surface-air interaction*
Piers Sellers:	*Problems with modeling and measuring biosphere-atmosphere exchanges of energy, water, and carbon on large scales*

Each presenter was asked to submit an abstract summarizing their talks. These are reproduced in the following material with minor editing. Lou Steyaert discussed a prototype land cover characteristics data base developed by the US Geological Survey. The US Geological Survey EROS Data Center, with support from the University of Nebraska-Lincoln, has developed a prototype land cover characteristics data base for the conterminous United States. Biweekly composites of 1 km AVHRR data for 1990 have been analyzed to define seasonally distinct land cover regions. The essential input to the classification process was vegetation greenness profiles as depicted by seasonal variations in the Normalized Difference Vegetation Index (NDVI) derived from daily AVHRR data. The

land cover characteristics data base is intended to meet the land data requirements of multiple-user communities such as those involved with land-atmosphere interactions modeling, land and water resource management, and environmental assessment. The data base includes the classification of 157 seasonally distinct land cover regions, biweekly AVHRR time-series data, various ancillary images (e.g., elevation, ecoregions, major land resource areas, and political boundaries), attribute data files providing summary statistics for each land cover class, and derivative data files (e.g., land cover classification systems, based on reclassification of the 157 classes, such as required by the Biosphere-Atmosphere-Transfer Scheme (BATS) and Simple Biosphere (SiB) models; greenness statistics on vegetation seasonality, etc.). Research is underway within the USGS to validate and test the land cover characteristics data base, including its use within global climate and mesoscale models, ecosystem dynamics models, soil biogeochemical cycles models, and ecotone models. These efforts complement ongoing research to improve AVHRR processing with enhanced geometric, radiometric, and atmospheric corrections. The integration of remote sensing and geographic information systems technologies with environmental simulation models is also under investigation. *After final review in early 1993, the prototype land cover characteristics data base will be placed on CD-ROM for distribution* and will complement biweekly AVHRR-image composite data for 1990, 1991, and 1992 now on CD-ROM.

Ray Arritt discussed the importance of inhomogeneous surface evapotranspiration on cumulus convection and its implications for mesoscale models. Land surface moisture is highly variable across a broad range of spatial scales from the continental scale to scales of centimeters or less. These surface moisture irregularities have several implications for the development of mesoscale convection and its representation in numerical models, including (1) local enhancement or suppression of surface sensible and latent heat fluxes; (2) generation of coherent mesoscale circulations that can trigger or suppress convection; and (3) alteration of the nature and statistics of turbulence in the convective boundary layer. Local modification of the surface sensible and latent heat fluxes can affect the magnitude of the conditional instability and can also determine whether the instability is released. The present consensus is that if the individual surface irregularities are of sufficiently small extent, their effects can be included by deriving a weighted average of the fluxes for the different surfaces. Finding average fluxes when the irregularities are larger is much more difficult. *The CME needs to investigate more general approaches for parameterizing surface sensible and latent heat fluxes that are appropriate for surfaces with both large and small moisture irregularities.* Horizontal variability of the surface sensible heat flux produces differential heating of the overlying atmosphere, which in some cases can drive coherent mesoscale circulations (Segal and Arritt 1992). The vertical velocities associated with these

circulations can trigger or suppress the release of conditional instability. *The CME presents an opportunity to expand upon our present inadequate knowledge of these circulations and to develop approaches for parameterizing their effects in mesoscale and larger-scale models.* To the extent that convective clouds are ``rooted'' in the boundary layer, the clouds will be influenced by the boundary-layer turbulence statistics and the characteristics of mixed-layer thermals. It seems reasonable to hypothesize that turbulence statistics may be affected by heterogeneity of the underlying surface, but observational data are inadequate to quantify this effect and numerical models usually disregard any such influence. Some cumulus parameterizations are sensitive to the initial updraft radius at cloud base (e.g., Kain and Fritsch 1990). Therefore, *the CME needs to investigate the linkage between boundary-layer thermals and the characteristics of the underlying surface.* For example, the possibility that the characteristic dimensions of the thermals reflect the dimensions of the surface moisture irregularities needs study. Large-eddy simulations can provide some insight into this relationship, but the LES results need to be corroborated by observations.

Mercedes Lakhtakia described the inclusion and applications of a surface-physics/soil-hydrology parameterization scheme into a modified version of a 1-D, high-resolution, moist PBL model (Zhang and Anthes 1982) within the Penn State/NCAR mesoscale model. The surface processes are simulated by a modified version of BATS, which provides a biophysically based representation of the surface forcing. The complexity of schemes like BATS not only increases the computational cost/time, but it also adds new dimensions to the initialization procedure. For instance, BATS requires the specification of the type of vegetation/surface cover and of soil texture, as well as the initialization of the soil-water-content profile for each grid point within the domain.

Chris Smith reported on the initialization of soil-water content in the Penn State/NCAR mesoscale model. *Soil-water content is the single most important land-surface variable in atmospheric prediction models.* Sophisticated surface physics-soil hydrology parameterization schemes are beginning to be used in mesoscale weather prediction models; however, soil-water content is not measured over large areas on a regular basis so as to provide suitable initial conditions for those models. Therefore, the initialization of the soil-water-content profile has to depend on a knowledge of the hydrological balance of the soil in the area represented by each mesoscale model grid point. In turn, this information must be obtained from a knowledge of the precipitation, evaporation, and substrate recharge from the water table. A systematic means for providing initial values of the soil-water-content profile for the PSU model is composed of three phases: (1) develop an "off line", 1D hydrological model that is driven by conventional meteorological, soil, and

vegetation data; (2) develop the data base to drive the hydrological model in a form that is compatible with the BATS surface physics-soil hydrology parameterization scheme utilized in the mesoscale model; and (3) generate an automated update of the soil-water-content profile at each of the mesoscale model grid points.

Conrad Ziegler discussed the impact of surface properties on dryline and MCS evolution. The dryline has long been acknowledged as a favored zone for thunderstorms and MCSs to form. The dryline-prone region (US High Plains) comprises roughly the western quarter of the Mississippi River Basin, which is a focus of the proposed GCIP experiment. A principle result of Ziegler's mesoscale modeling study is that the horizontal variability of soil moisture controls sensible and latent heat fluxes through the atmospheric surface layer, which in turn governs whether a dryline forms and how it evolves. Over periods of many weeks, successive dryline passages and convective rainfalls might selectively enhance soil moisture and surface heat flux gradients, which in turn would enhance the dryline. *There is a critical need for time-series measurements of soil moisture profiles to complement other mesoscale data in the dryline-prone region.*

Zu-Tzai Soong simulated a flood in the Sacramento Valley using a mesoscale model with a 20 km resolution and containing ice microphysics, radiation, and soil / surface / boundary layer processes (the Oregon State University module). This module was tested against HAPEX (Hydrological/Atmospheric Pilot Experiment) observations and, though comparatively simple, it is believed adequate, and is both easy to implement and run. Of course, a more complete model like SiB or BATS is more desirable for future model implementations. The simulated total precipitation of the mesoscale model over the northern Sierra was close to the observed maximum. One direction of future coupled atmospheric-hydrologic models is to study the moisture budget over a large river basin, such as the Mississippi and the Colorado River basin. The model should also be coupled with a river flow model to study the river flow hydrology.

Roni Avissar reported on the parameterization of land-atmosphere interactions in large-scale atmospheric models. Land heterogeneities affect considerably the redistribution of energy absorbed at the surface of the earth and atmospheric dynamical processes at various scales. Among the various land-surface parameters that characterize a landscape, Collins and Avissar (1992) found that stomatal conductance, leaf area index, and surface roughness have a predominant impact on the turbulent heat fluxes between vegetated surfaces and the atmospheric surface layer. For bare land, they found that the most important parameters are soil-surface wetness and surface roughness. The microscale

spatial variability of these parameters (as observed in the field) affect significantly the integrated surface energy fluxes at the patch scale, emphasizing the need to develop statistical-dynamical parameterizations for atmospheric models. Heat and mass fluxes associated with mesoscale circulations generated by landscape discontinuities are typically stronger than turbulent fluxes. As a result, they contribute significantly to subgrid-scale fluxes in large-scale atmospheric models (e.g., GCMs), yet are omitted in these models. Avissar and Chen (1992) suggested a set of prognostic equations for large-scale atmospheric models, which accounts for both turbulent and mesoscale subgrid-scale fluxes. They also developed prognostic equations for the mesoscale fluxes, which present a closure problem. Thus, they emphasized the need to develop a parameterization for these fluxes and identified the mesoscale kinetic energy (MKE) as a possible key variable for such a parameterization. Chen and Avissar (1992) used a state-of-the-art mesoscale model to investigate the relationships between mesoscale fluxes, turbulent fluxes, and the spatial distribution of land-surface wetness. These relationships are characterized by analytical functions, which provide a crude primary parameterization of mesoscale fluxes for large-scale models.

Pete Wetzel made three major points with regard to the role of sub-grid heterogeneity in the modeling of land-atmosphere interactions.

- Evapotranspiration modeling presents the most serious challenge because of its complexity.

Observations have shown significant heterogeneity of soil moisture even down to scales of the individual field. Modeling results have shown that failure to account for this heterogeneity leads to erroneous model estimates of regional evapotranspiration. The heterogeneity of vegetation, topography, and, on larger scales, precipitation only add to the degree of heterogeneity which affect regional evapotranspiration. Further, within any mesoscale or GCM model grid cell it is likely that both water-stressed and unstressed (potential) evapotranspiration will be occuring simultaneously in different portions of the cell, both over bare soil and vegetation covered areas. Thus there are four fundamentally different and unrelated processes which affect evapotranspiration. Again, modeling results show that lumping these processes together can lead to unrealistic regional evapotranspiration estimates.

- Results from Wetzel's 1-D PLACE model (Parameterization for Land-Atmosphere-Cloud Exchange), demonstrate that explicit modeling of the fully interactive relationship between the heterogeneous surface, boundary layer and cloud can lead to more accurate predictions of cloud onset and amount over land surfaces.

Surface variability plays a fundamental role in defining the statistical thermodynamic properties of cloud updrafts. Accounting for this heterogeneity markedly improves the predictability of cloud onset time and amount. Within a 48 hour period, the relationship between soil moisture and resultant cloud amount can be completely reversed--that is, where wet soil produces much more afternoon cloud on the first day, the dry soil case is found to produce much more cloudiness 48 hours later.

- Additional PLACE model results indicate that, depending on its distribution and concentration, a given amount of sub-grid precipitation falling on a model grid cell can be primarily re-evaporated (if distributed evenly) will primarily soak into the soil (if distributed with a moderate degree of sub-grid variability), or will primarily run off (when the rain falls as concentrated, heavy downpours).

This fairly intuitive result has especially serious ramifications for modeling of river discharge and of the climatological water balance of a region. It provides a strong motivation for the development of more sophisticated deep cumulus parameterizations which, in turn (see point 2) should account for the surface heterogeneity.

Piers Sellers reported on results from FIFE and the use of models and satellite data to calculate heat, moisture, and carbon fluxes on large scales. Specification of the land surface-atmosphere fluxes of energy, water, and carbon is important for a wide range of atmospheric and Earth System modeling activities. It has been shown that the canopy conductance (inverse of resistance) is a critical term in determining the partitioning of available energy into sensible and latent heat (evapotranspiration) and also in regulating the flux of carbon dioxide into the vegetation for photosynthesis. The Penman-Monteith equation defines the latent heat flux as controlled by the available energy, the vapor pressure deficit, and the surface conductance. When the upper few millimeters of the soil profile is dry, the vegetation contribution to the latent heat flux dominates. Sellers and colleagues have developed a theoretical framework that relates the derivative of the unstressed canopy conductance with respect to the incident photosynthetically active radiation (PAR) to the fraction of PAR absorbed by the green vegetation canopy, FPAR. FPAR has been shown to be a near-linear function of the simple ratio vegetation index (SR), which is the ratio of the near- infrared to red reflectances (or radiances) as observed by a suitably configured remote sensing device, e.g., Landsat or Advanced Very High Resolution Radiometer (AVHRR).

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3.7 Incorporation of the planetary boundary layer in atmospheric models

Chin-Hoh Moeng: Evaluation and development of planetary boundary layer models in mesoscale and global climate models

John Wyngaard: *Perspectives on planetary boundary layer (PBL) measurements*
Roger Pielke: *Current problems of PBL parameterization in mesoscale models*
Steve Krueger: *Convective cloud-PBL interactions*

The planetary boundary layer (PBL) plays a crucial role in coupled mesoscale systems, because of its importance in transporting momentum, heat, and moisture from the surface into the systems. One must therefore accurately incorporate these PBL processes into coupled mesoscale models. Chin-Hoh Moeng introduced the colloquium participants to the PBL Model Evaluation and Development Project at NCAR. This PBL project, initiated by John Wyngaard and Peter Taylor on request by the World Meteorological Organization, is aimed at finding the most promising PBL schemes for coupled climate models. *It is highly desirable to similarly evaluate PBL schemes used in (coupled) mesoscale models.* The approach for climate applications is the following:

- Survey, review, and code six generic PBL parameterizations currently used in GCMs (R_i-dependent diffusion coefficient, single-point closure, K-profile, mixed-layer, multi-stream exchange (including transilient, Blackadar, and mass flux models), and stability-bounded models).
- Generate a database through large-eddy simulations (LESs) of different types of PBL.
- Evaluate the performance of the six models against the LES database and available observations.
- Develop the most promising PBL parameterizations for an atmosphere-ocean coupled GCM.

Over the past two years, the working group has focused on developing a PBL evaluation software package and generating the LES database. So far, the software package includes most of the above-mentioned generic PBL models, and the database consists of nine different PBL cases (including highly convective, weakly convective with strong shear, pure shear, and stratus-topped PBLs.). Both baroclinic and stable PBLs are now being simulated. Even though this PBL package and the LES database were developed for climate study, they can be used for mesoscale studies as well. Which key PBL parameters should be emphasized is the main difference between climate and mesoscale applications. In mesoscale modeling, the vertical distributions of temperature and moisture within the PBL could be important since the models may explicitly resolve cloud formation. The wind direction within the PBL can also be crucial for some mesoscale system developments. Both

explicit and implicit interactions between PBL and cumulus systems have to be considered since in mesoscale modeling some cumulus clouds are resolved and some are subgrid scales. Third, many mesoscale system developments are strongly affected by heterogeneous surface conditions; the PBL scheme has to be able to transfer these effects to the mesoscale developments. *The LES database is limited to horizontally homogeneous PBL types. We must depend on observations for more complicated PBL cases. The Cooperative Multiscale Experiment hopefully will provide a useful dataset for this type of study.*

John Wyngaard discussed three historical developments which have shaped the present state of PBL meteorology:

- "Acoustic sounding" (e.g., McAllister et al. 1969) led directly to more realistic PBL models by revealing the sharp top of the growing convective boundary layer and vivid details of the eddies within it. These data led to more realistic PBL models, which at the time had predominantly tended to portray the PBL top as diffuse

- These developments fostered the growth of numerical modeling as a research medium, including three-dimensional numerical modeling (Deardorff 1973) (later renamed large-eddy simulation, or LES) and second-order closure, which was appealing and much cheaper than LES (e.g., Donaldson 1973). Such applications showed that models must be "tuned"---their closures adjusted---for different geophysical flows, and hopes for a "universal" turbulence model faded.

- The role of meticulous, quantitative observational work has diminished. This has occurred despite the fact that observationalists had extraordinary success in documenting the surface layer, filling out the details of Monin-Obukhov similarity theory, exploring second-moment budgets, mapping out spectral behavior, and making detailed measurements of the stability dependence of the mean wind and temperature profiles and their surface-exchange coefficients. Unfortunately, when they began to extend these measurements throughout the PBL, their data had much more scatter than in the surface layer, due not only to the more complicated and variable physics of the outer layers, but also to the "inherent uncertainty"---the scatter between a local time or space average and the ensemble average. Obtaining the data for tuning a model of the outer PBL, or the stably stratified boundary layer, or the interfacial layer, or the cloud-topped mixed layer, was very difficult, perhaps even impossible, and also very expensive.

Wyngaard stressed that PBL models have not been tuned (tested) extensively, due to the lack of suitable data, but also because the importance of tuning is not agreed upon. Some see it as essential because models are not predictive tools (e.g., Lumley 1990), whereas others clearly regard most models as inherently trustworthy. Numerical *simulation* using the governing equations is growing rapidly in the turbulence community, particularly for generating benchmark data for developing and calibrating turbulence *models* (which use approximations). By contrast, the decline of observational work in PBL flows is restricting the flow of data for model development and limiting the supply of well trained, new observationalists. *Progress has been slow on the question of the influence of mesoscale*

variability on PBL and turbulence statistics. Without many samples of the mesoscale contribution, the PBL measurements will have large random errors. A critical unresolved question is whether large-scale meteorological and oceanographic models (mesoscale to global), which use submodels of the PBL, are really faithful to our understanding of the physics. We do not know, because few if any of these PBL submodels have ever been systematically and rigorously evaluated. The NCAR PBL Model Evaluation and Development Project aims to evaluate these submodels and to develop improved ones. To do this we need to develop a comprehensive data base for testing them and for inspiring the development of better ones, since direct observations cannot provide all the data we need; we must supplement them with simulation results and laboratory data. Furthermore, we must decide which issues can be addressed through observations and which cannot, and we need to design our field programs accordingly. The same judgments need to be made about numerical simulation. Funds should be provided not only for carrying out field programs, but also for their design and for the analysis of their data.

The next speaker in this session was Roger Pielke, who discussed current and related problems of PBL parameterization in mesoscale models. *He echoed the concern that the parameterization of boundary layer processes for use in larger scale models has been based almost exclusively on observations collected for horizontally homogeneous surface conditions under simple, slowly time-varying synoptic weather conditions.* Meanwhile, actual surface and atmospheric forcing is generally not so idealized. Among the main issues to be investigated in developing a more general parameterization are:

- How large does a surface heterogeneity have to be before the horizontally-homogeneous boundary layer parameterization fails? The concept of blending height has been introduced to describe this concept.
- When this parameterization fails to adequately represent heat, moisture, trace gas, and/or momentum fluxes, how important are coherent circulations vis`a-vis turbulence fluxes of these quantities?
- Since existing horizontally homogeneous parameterizations of boundary layer structure are based on time-averaged data (e.g., 20 minutes), how important are variations of similarity and mixed layer scaling parameters on the time scale of the larger scale model (i.e., the time step)? It is unknown whether these variations in what are an ensemble-based boundary layer parameterization result in significantly different larger scale model realizations.
- How do we represent rapidly-changing boundary layer structure such as occurs in the vicinity of atmospheric features like deep cumulus convection? It may be that the boundary layer fluxes are much more important at preconditioning the potentially cumulus convective environment, as contrasted with its importance during the mature stage of these storms.
- What level of complexity is required to accurately represent the coupling between biophysical and boundary layer processes? The stomatal conductance of water vapor to the atmosphere is already

known to be strongly coupled to incoming radiation (which is influenced by clouds, etc.), temperature and humidity at the plant leaf surfaces, etc.

The last speaker in this session was Steven Krueger, who talked on the topic of convective cloud-PBL interactions and its parameterization, both in terms of PBL interaction with shallow, non-precipitating cumuli and its interaction with deep, precipitating convection. Shallow cumuli are often considered to be boundary layer turbulence, while deep cumuli are clearly separated in scale from boundary layer turbulence. Cumulus-PBL interactions consist of boundary layer controls on convection initiation, intensity, and organization, as well as cumulus feedbacks on the boundary layer. The boundary layer controls convection through cumulus updraft properties, the boundary layer depth, and boundary layer convergence zones including gust fronts, horizontal rolls, and sea breezes. Cumulus convection affects the boundary layer through compensating subsidence, cumulus fluxes due to updrafts (if cloud roots exist), penetrating downdrafts, rain evaporation, and the radiative effects of cumulus clouds. Cumulus circulations in the boundary layer also affect the surface fluxes of sensible and latent heat. Parameterizations for shallow cumulus-PBL interaction include Albrecht's trade cumulus-specific model which is a two-layer model with a mixed subcloud layer and an unmixed cloud layer, and where the fluxes in the cloud layer are based on a convective mass flux model. Bougeault's third-order closure model is more general, since it includes a condensation parameterization that depends on third-order moments (though they are not very reliable). Bougeault's model could be coupled to a deep convection parameterization if the boundary layer model only operates on the atmosphere after it has been stabilized by the deep convection parameterization.

Parameterizations for deep cumulus-PBL interaction include those designed for GCMs and those designed for mesoscale models. Deep convection often becomes organized into mesoscale convective systems (MCSs). This makes modeling the cumulus-PBL interactions different in GCMs and mesoscale models. In a GCM, convection depends on the existence of destabilizing large-scale processes in the presence of conditional instability. In a mesoscale model, the destabilizing processes may be mesoscale circulations primarily forced by (parameterized) convection. The principal boundary layer features of an MCS are cool, dry convective downdrafts and a mesoscale "wake" of downdraft air. In a GCM, the time and space scales of mesoscale wakes may be sufficiently small so that the wakes may be essentially ignored. The restoration process is fast enough that only the undisturbed state need be modeled. Another motivation for this is that updraft air (usually assumed to have the mean subcloud layer properties) typically does not come from the wakes; it comes from

undisturbed regions. The Arakawa-Schubert-Cheng (ASC) cumulus parameterization (Cheng and Arakwa 1990) is an example of a parameterization appropriate for GCMs, in which convective downdrafts were added to the original Arakawa-Schubert parameterization. Sarachik (1974) noted that the vertical mass flux in the environment of the cumulus clouds should be consistent with observed mixed layer depths. Later comparisons indicated that neglect of convective downdrafts in diagnostic models of cumulus ensembles leads to excessive diagnosed compensating subsidence in the environment compared to that deduced from observed mixed layer depths. The ASC scheme is coupled to a mixed layer model, in which the mixed layer height evolves due to entrainment, cumulus subsidence and large scale vertical motion. Cumulus updrafts start with mean mixed layer properties. Cumulus downdrafts can detrain into the mixed layer, but their thermodynamic effects are assumed to be locally compensated by enhanced sensible and latent heat fluxes from the surface. An alternative model of the undisturbed mixed layer (between wakes) which takes into account the inflow of relatively cool downdraft air into these undisturbed regions was proposed by Johnson (1981). This model requires knowledge about the average properties of the downdraft air, as well as how these properties are modified within the wake region by sensible and latent heat fluxes from the surface. During periods of active deep convection in GATE, environmental subsidence (away from cumulus clouds and mesoscale downdraft systems) is weak, yet the mixed layer there does not grow rapidly because of the inversion-strengthening effect of cool downdraft air outflow into the undisturbed regions.

Mesoscale cumulus parameterizations should parameterize convective downdrafts that detrain into the boundary layer. The boundary layer model used must recognize the downdraft effects and be able to simulate the recovery of a wake. Mixed layer models appear to be adequate for this (Fitzjarrald and Garstang 1981; Nicholls and Johnson 1984). In such a model, the parameterized convection will respond to the explicit mesoscale forcing (including boundary layer convergence zones) and mesoscale variations of boundary layer properties. Cloud scale models resolve the cloud-scale and mesoscale variations in boundary layer properties. Thus, modeling the evolution of the boundary layer is primarily limited by the realism of the turbulence closure and surface flux models. In such models, convection will be initiated by resolved cloud scale circulations (including boundary layer convergence zones) and cloud scale variations of boundary layer properties.

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3.8 The role of radiation in mesoscale flows: physics, parameterizations, codes

P. J. Flatau: Review of radiation parameterization for mesoscale models

Dean Churchill: *An overview of radiation and mesoscale flows*
Robert D. Cess: *Lessons learned from the intercomparison of GCM radiative codes*

Piotr Flatau discussed three issues in his keynote talk on radiative transfer parameterizations for mesoscale models:

- How mesoscale processes influence climate by interaction of extensive stratiform cloudiness, cirrus debris, and increased moisture with the radiative field
- The importance of cloud microphysical/radiation processes (such as changes in particle shape and size, varying refractive index, and changes in albedo) in mesoscale dynamics
- Which local processes (e.g., convection, turbulence, entrainment fluxes, and evaporation) are most influenced by radiative fluxes, and what time scales are involved

He suggested that, knowing what the issues are, one is faced with several technical problems, including what optical properties to measure and observe, and whether we can transform our knowledge about the radiative properties of MCSs and mesoscale phenomena into consistent radiative transfer parameterization. It is also essential to consider how to convincingly present results from mesoscale models and field studies in their more global climate context, and how experiences in other radiation and climate related projects (ARM, FIRE (Starr 1990), etc.) could contribute to the design of the CME field project. Flatau then discussed several topics related to radiative parameterizations and cloud microphysics, including assumptions needed to develop a two-stream approximation to the radiative transfer equation, assumptions needed to get single scattering properties such as single scattering albedo and asymmetry parameter, and coupling of radiative transfer with particle size distributions through averaged single scattering properties. It is possible, he concluded, to tie properties such as irregular cirrus particles, inhomogeneous particles, and particles with refractive index other than that of water or ice (aerosols, chemistry) to radiative transfer schemes but only at a cost comparable to that of explicit microphysical schemes. Current theoretical approaches of single scattering parameterizations consist of anomalous diffraction theory, power law fits to Mie calculations, and table look-ups. Theoretical approaches for scattering calculations on non-spherical particles presently consist of discrete dipole approximation, ray-tracing, and multipole methods. These are costly calculations not suitable for parameterizations in their current form. Flatau also discussed the unified approach to radiative transfer solvers showing that all existing schemes reduce to the banded (blocked) type linear problem. As

for the infrared emissivity approach, the mesoscale radiative transfer differs from solvers employed in GCMs because more details are available in mesoscale models. This presentation concluded with the presentation of several current radiative transfer schemes in use.

Dean Churchill's presentation concentrated on the phenomenology of mesoscale flows as influenced by radiation. He gave a short summary of interactions between radiation and cloud physics, radiation and dynamics, and radiation and convection. He discussed Houze's (1989) paper stressing the differences between convective and stratified parts of mesoscale convective systems and their implications for large-scale heating. He then reviewed the work of Churchill (1992) discussing the role of solar and infrared radiation in stratified regions of tropical cloud clusters (an EMEX case study), and that of Churchill and Houze (1991) concerning the interaction between turbulence and radiation. Finally, he mentioned some implications of mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate (Hartman et al. 1984).

Robert Cess discussed lessons learned from the intercomparisons of GCM radiative transfer codes. He discussed an international project to isolate and understand interactive processes in general circulation models as well as in observational data. To date 12 GCMs have been used to produce 24 simulations of global warming caused by a doubling of atmospheric carbon dioxide. Cess enumerated possible reasons for model disagreement, namely differences in radiation codes, differences in atmospheric temperature structure, differences in radiative overlap by atmospheric water vapor, differences in the radiative impact of clouds, and coding errors. He warned to "never adjust more than one thing at a time or it will be impossible to tell which adjustment produced what result".

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3.9 Chemistry on the mesoscale: modeling and measurement issues

Anne Thompson

John Pleim:	*RADM - A coupled chemistry/mesoscale model*
Christopher Walcek:	*Convection in RADM (Regional Acid Deposition Model)*
Jason Ching:	*Unresolved issues for mesoscale modeling with chemistry: non-precipitating clouds*
Frank Binkowski:	*Unresolved issues for mesoscale modeling with chemistry: aerosols*
Wei-Kuo Tao:	*Tracer Studies with GCEM (Goddard Cumulus Ensemble Model)*
Russell Dickerson:	*Field observations of trace gas transport in convection*
Kenneth Pickering:	*Photochemical consequences of convection*

The talks in this session pointed out that we have only begun to investigate the consequences of mesoscale meteorological features for atmospheric chemistry. *Uncertainties that exist in many modules of regional and cloud-scale chemical models could be reduced by incorporating chemical measurements and modeling into a Coordinated Multiscale Experiment (CME). Conversely, the use of chemical tracers in a CME can much better define air motions on both cloud and mesoscale.*

Jonathan Pleim discussed the various applications of the RADM (Regional Acid Deposition Model) coupled chemistry/mesoscale model and issues such as the amount of cloud cover produced by the model, PBL processes, biosphere/atmosphere interactions, and subgrid-scale photochemistry. Chris Walcek then presented the transilient matrix convective parameterization that is now in one version of RADM. Jason Ching and Frank Binkowski emphasized unresolved issues for mesoscale chemistry modeling, with regards to nonprecipitating clouds and aerosols, respectively. In particular, Ching discussed parameterizing the fraction of boundary layer air that is vented to the free troposphere by nonprecipitating clouds, describing the modeling of cumuli as flow through chemical reactors. Binkowski discussed development of the Regional Particulate Model, which will facilitate studies of the distribution of sulfate particles, with particular emphasis on the importance of ammonia. Wei-Kuo Tao described the GCEM (NASA/Goddard Cumulus Ensemble Model) and an associated tracer advection model, and showed a video tape of the 3-D redistribution of CO by a major squall line. Russell Dickerson's talk was concerned principally with aircraft chemical observation capabilities for a multiscale experiment, and he showed observations of stratosphere/troposphere exchange in a major MCS. Kenneth Pickering summarized convective enhancement of ozone production in the free troposphere for several case studies, and also showed possible flight strategies for verifying tracer and photochemical model results.

These talks all reviewed the current knowledge and research needs for chemistry on the meso and cloud scales. These needs closely parallel recommendations of a National Research Council (NRC, 1992) report which focuses on the ozone pollution problem in the U. S.. The NRC report points out that tropospheric ozone is a multiscale problem (urban, regional, global) and emphasizes that treatments of surface and boundary layer processes (including natural HC emissions from vegetation) and cloud venting are required for understanding the production and distribution of ozone in the troposphere.

1) Coupled Chemistry/Atmospheric Models

Although coupled models are now available for scales ranging from cumulus cloud scale to global scale, the colloquium emphasized coupled cloud scale and mesoscale (regional) models.

- *Regional models*

One coupled mesoscale-chemical model is the Regional Acid Deposition Model (RADM), which was developed during the 1980's to study source-receptor relationships between pollution emission and acid deposition [Chang et al. (1987); Walcek et al. (1990); Pleim et al. (1991); Pleim and Chang (1992)]. The model now resides at the Environmental Protection Agency in Research Triangle Park, NC, but versions exist at the State University of New York at Albany for a variety of atmospheric chemistry applications. Advection and dispersion of pollutants in RADM is driven by meteorological fields produced by the MM4 version of the Penn State/NCAR Mesoscale Model. Considerable effort was employed in developing the RADM chemical mechanism, although other mechanisms may be substituted into the model. Two model components in particular that are fairly crude and require additional work: (1) parameterizations of surface and boundary layer processes, and (2) parameterizations of boundary layer venting by convective clouds. Surface and boundary layer processes represent important components of the budgets of many trace species. For example, vertical fluxes of species such as HNO_3 are critical in estimating dry deposition of acidic material to surfaces. Emissions of natural hydrocarbons from vegetation are important in determining the amount of ozone production in some regions. The methods of determining the top of the mixed layer and its diurnal variation in the model have critical chemical implications because the depth of the mixed layer determines the initial volume into which pollutant gases and aerosols are mixed. Similarly, convective motions rapidly redistribute heat, momentum, moisture and trace chemicals in conditionally unstable areas. In addition, precipitation formed by condensation and coalescence removes water substance from the atmosphere, and latent heat resulting from this removal warms the atmospheric column. These mixing and condensation processes are initiated by nonhydrostatic, buoyancy-induced, cloud-scale dynamics. Any numerical models employing a horizontal resolution greater than ~10 km cannot resolve these processes. As a result, larger-scale models of atmospheric processes must parameterize these processes based on some assumed relationships between the convective-scale processes and resolvable processes.

Other significant uncertainties in coupled multiscale modeling associated with clouds include radiative effects, heterogeneous chemistry, and production of NO_x by lightning.

Perturbations of photolysis rates in and near clouds significantly alter the ozone production chemistry [Thompson 1984]. Some aqueous reaction schemes (e.g., Lelieveld and Crutzen 1990) show reduction of ozone production in clouds due to heterogeneous processes. Field observations are necessary to verify these theoretical calculations. NO_x production by lightning remains a large uncertainty because of the wide range of emissions per lightning flash that have been measured and because the number of intracloud and cloud-to-cloud flashes have generally not been counted.

- *Cloud models*

Cho et al. (1989) developed a coupled convective cloud model with gas and aqueous phase chemistry and fairly detailed microphysics, designed primarily for acid deposition studies. Chatfield and Delany (1990) developed a convective cloud/chemistry model that primarily simulates convective redistribution and fairly complete ozone photochemistry. Both of these models are essentially one-dimensional models designed for eventual incorporation into 3-D Eulerian transport/chemistry models.

Estimation of ozone formation in the free troposphere after redistribution of precursor gases by deep convection has been the objective of Pickering and coworkers at NASA/GSFC (Pickering et al. 1992c). These studies are based on running convective cloud and photochemical models in tandem. The detailed 2-D GCEM model (e.g., Tao et al. 1991) is run to simulate a particular deep convective event and wind fields generated by this model are used to advect and disperse the trace gases. Subsequently, particular profiles from the 2-D trace gas fields are used in a 1-D photochemical model (e.g., Thompson and Cicerone 1986) to estimate ozone production rates in cloud processed air. The largest uncertainties associated with this model stem from the treatment of the boundary layer, the representation of cloud microphysics and radiational characteristics, and the lack of interaction with meso- or larger-scale processes. For example, the only surface characteristics represented in the model are surface fluxes of heat and moisture. The photochemical model can either be run with photolysis rates for a clear sky or for the case of a single slab cloud, obviously an oversimplification of the real atmosphere.

2) *Chemical effects*

- *Ozone Production*

Deep convective clouds are a major means of transporting insoluble O_3 precursor gases (e.g. CO, NO_x, and hydrocarbons) from the boundary layer to the middle and upper troposphere [Dickerson et al. 1987; Luke et al. 1992]. These species, once detrained from a convective cloud, can react to produce O_3 in the free troposphere downwind from a convective system. (Note that O_3 in the upper troposphere is an effective greenhouse gas [Fishman et al 1979].) Because of higher winds and a longer photochemical lifetime than it has in the boundary layer, O_3 in the free troposphere may be transported large distances from the precursor source region [Pickering et al 1989]. More important, O_3 production in the boundary layer may actually be more efficient following dilution of polluted boundary layer air by deep convection when cleaner air descends in downdrafts. In this case the potential for O_3 production in the entire tropospheric column is enhanced. The major factors affecting the degree of enhancement of O_3 production by convection are the available boundary layer NO_x, strength and structure of the convective cells, presence of lightning-generated NO_x and the amount of background pollution in the free troposphere. An example of convective redistribution of NO_x and its consequences for O_3 production is given in Fig. 12 [Pickering et al 1992b]. The illustrations are all model-derived analyses of an episode from NASA/GTE/ABLE 2B, with pre-convective profiles of NO_x based on measurements. *There have been very few research flights with extensive sampling of cloud-outflow air to confirm such model predictions of convective transport and of O_3 production rates in cloud-processed air.*

Some fraction of nonprecipitating cumulus clouds also transport trace gases from the boundary layer to the free troposphere. Because these clouds do not typically occur in an organized weather system, their overall effectiveness for vertical transport is much more difficult to determine. Ching and Alkezwenny (1986) investigated the transport properties of a field of cumulus using SF_6 as a tracer and Ching et al. (1988) observed significant vertical exchange of ozone and aerosols between the mixed layer and the free troposphere during cumulus cloud activity using an airborne UV-DIAL system. Vukovich and Ching (1990) developed an empirical approach to estimate vertical transport by an ensemble of nonprecipitating convective clouds in a regional oxidant model. Very little verification data are available for this algorithm.

On a regional basis over a season, deep convection in the tropics may vent a significant fraction of CO, NO_x and hydrocarbon emissions from biomass burning to the free troposphere [Pickering et al 1992a]. It is clear that parameterizations of deep convection in 3-D global and regional chemical models need to capture chemical consequences of convective redistribution.

- *Aerosol-heterogeneous chemistry*

Over the eastern and central U. S. sulfates are a major, if not dominant, aerosol particle species. Water content and optical characteristics of clouds are crucially dependent upon the NH_4^+/SO_4^{--} molar ratio. Cumulus clouds are major chemical reactors where SO_2 gas is transformed into sulfate aerosol. Anecdotal data have suggested that the sulfate is not completely neutralized; thus, field studies are necessary to evaluate the level of neutralization of the aerosol and the amount of sulfate production in nonprecipitating cumulus clouds. These processes must be further elucidated in support of the development and validation of a Regional Particulate Model that will be adapted from RADM.

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3.10 Validation of mesoscale models

Bill Kuo: Verification of mesoscale models

Tom Warner:	*Verification of cloud prediction from the PSU/NCAR mesoscale model*
Stan Benjamin:	*Results from MAPS/NGM verification comparisons and MAPS observation sensitivity tests to ACARS and profiler data*
Steve Koch:	*Systematic errors and mesoscale verification for a mesoscale model*
Andrew Staniforth:	*The COMPARE Project and the CME*

Bill Kuo opened the session by giving a review on the general methodologies used in the verification of mesoscale models. He then described the recent verification of an experimental mesoscale numerical weather prediction model during STORM-FEST, in which a 20-km version of the PSU/NCAR mesoscale model was used to provide experimental numerical guidance. His results showed that this model (which was not tuned prior to its use in support of STORM-FEST) gave a superior performance over the NMC Nested Grid Model (NGM). *This indicates that a mesoscale model which employs advanced physical parameterizations and more realistic topography has a strong potential to improve short-range local forecasting.* By verifying the model forecasts against the three-hour special rawinsondes and hourly profiler observations, Kuo was able to examine the model's systematic biases. He showed that the PSU/NCAR model has a wet bias in the humidity fields above 500 mb. By 36-h, the accumulated positive bias can be as high as 30%. He also noted that the model has a weaker diurnal variation in the surface-air temperature than that shown by the surface station observations. These results showed that *further improvement in model precipitation and planetary-boundary-layer parameterization is needed.*

Tom Warner presented a study on the verification of cloud prediction from the PSU/NCAR mesoscale model, wherein model-predicted cloud cover (based on relative humidity and cloud water) were compared against the Air Force real-time Nephanalysis of cloud cover over 20 days. Predictions of the vertical distribution of clouds were found to contain significant biases. Although the total cloud-cover bias scores were reasonably good in general, the model has less skill for "scattered" and "broken" coverage, and higher skill for mostly clear or mostly cloudy conditions. *The use of model-predicted cloud water as a predictor of cloud fraction shows promise.*

Stan Benjamin discussed the results from verification comparisons between the MAPS (Mesoscale Atmospheric Prediction System) and NGM models, with emphasis on the impact of ACARS and profiler data on short-range forecasts. Based on verification against rawinsonde observations, he showed that MAPS 3-h and 6-h forecasts are superior to 12-h forecasts from NGM at most levels. This difference is most pronounced for wind forecasts near jet levels. Observational sensitivity tests presented also showed that ACARS-reported observations from commercial aircraft are the most important asynoptic observation for improving short-range forecasts over the United States at the current time. However, the observations from wind profilers also provide a smaller but consistent improvement to wind and height forecasts. Based on the statistical verification of a large number of cases against both point observations and grid data, Benjamin concluded that verification against point observations were less ambiguous because of independence from the objective analysis scheme used and less scale dependence. He emphasized that *the key element in verifying mesoscale forecasts is the availability of mesoscale observations.*

Steve Koch gave a presentation on systematic errors and mesoscale verification of the Mesoscale Atmospheric Simulation System (MASS). Although he conducted this assessment nearly a decade ago, it still serves as an exemplary approach to model validation, this being the first known attempt to systematically evaluate the ability of a modeling system to predict MCS activity without resorting to the usual case study "tuning" approach. Nearly 30 simulations were evaluated, first for their systematic errors at the synoptic scale, and then for their accuracy in "predicting" MCS likelihood in terms of convective predictor fields (the model at that time did not explicitly predict convective precipitation), verified against Manually Digitized Radar (MDR) data. Clearly, were one to perform a similar evaluation today, this method should be modernized to use digitized NEXRAD data and explicit model prediction of convective precipitation. Nonetheless, an important result of the model evaluation was that *systematic errors in predicted synoptic-scale fields adversely affected the model's ability to "predict" MCSs.* In particular, the evaluation revealed errors

in the model map transformation and boundary condition codes, inadequacies in the initialization of moisture over and near the Gulf of Mexico, and the need to include a convective parameterization scheme in the model to avoid systematic thickness errors. An interesting use of the temporal behavior in model forecast error statistics was shown to be uniquely capable of revealing certain systematic errors.

Andrew Staniforth described an international community effort in the verification of mesoscale models--the COMPARE (Comparison of Model Prediction and Research Experiments) Project under the auspices of the CAS/JSC Working Group on Numerical Experimentation. Recherche en Prevision Numerique of Environment Canada has taken the lead in this effort. The idea is to compare in a controlled way the results of many mesoscale models (and eventually mesoscale data assimilation systems) from both research and operational communities, on a representative testbed of cases selected primarily from Intensive Observation Periods of well-instrumented observational campaigns. Through model and data assimilation intercomparisons, they hope to improve communication among modelers, increase understanding of mesoscale phenomena and predictability, and improve the performance of various components of mesoscale models (particularly parameterizations) and mesoscale data assimilation systems, leading ultimately to improved models for both operational forecasting and research applications. The first case chosen for this project is the March 6-8, 1986 IOP of the Canadian/US CASP/GALE (Canadian Atlantic Storms Project/Genesis of Atlantic Lows Experiment) field study. The common data set (stemming from a regional reanalysis of the observed data, and using a "standardized" data-distribution format to facilitate the distribution of future cases) has recently been distributed to participants to initialize their models and make forecasts. A workshop is planned for the Spring of 1994 to discuss the ensuing results. The preparation of a second case, an IOP drawn from the Franco- Spanish PYREX field study, is underway, and the selection of further cases is under discussion. *The chairman of COMPARE ended his presentation by inviting the organizers of the CME to consider collaborating with the COMPARE project by providing a set of scientific hypotheses to be verified by coordinated numerical experimentation using data and analyses drawn from a CME IOP.*

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3.11 Techniques and resources for storm-scale numerical weather prediction

Kelvin Droegemeier: Non-hydrostatic modeling and prediction in the mid-1990's and beyond: strategies for dealing with data, parallel processors, and communication

Georg Grell: Multi-scale application of the 5th-generation PSU/NCAR mesoscale model

James Doyle:	*The coupling of non-hydrostatic atmospheric and hydrostatic ocean models for air-sea interaction studies*
Su-Tzai Soong:	*A numerical simulation of cloud formation over complex topography*
William Skamarock:	*Adaptive grid simulations of convection*
David Bacon:	*An unstructured grid, non-hydrostatic meso/cloud scale model*
Andrew Staniforth:	*Efficient mesoscale modeling for multiple scales using variable resolution*
Andrew Crook:	*Initialization of cloud-scale models with Doppler radar data*
Robert Wilhelmson:	*Making effective use of future computing architectures, networks, and visualization software*

The keynote presentation by Kelvin Droegemeier outlined the principal challenges associated with operational storm-scale prediction. With regard to data access, the realtime collection and processing of WSR-88D data will require high-bandwidth networks and relatively sophisticated database management systems; little work has been performed to date in either of these areas. Numerical models continue to evolve and mature, and adaptive grid refinement appears to show great promise for providing selectively enhanced spatial resolution in critical regions of the flow. *The major areas of difficulty in modeling center around accurate characterization of surface features and processes and obtaining quantitative information on water substance fields.* Data assimilation methods are receiving considerable attention in the scientific community, and the adjoint technique, though still relatively expensive, appears suitable for application to moist processes (e.g., the tangent linear approach), though application to storm-scale prediction has not yet been attempted. Finally, although massively parallel computers continue to be made available, the realized performance for most codes is far below machine peak due to the absence of suitable translation tools. The advent of Fortran-P and High Performance Fortran should help alleviate this problem, though it will likely be some time before production scientific experiments are run on MPP's on a regular basis.

Georg Grell introduced the fith generation of the PSU/NCAR mesoscale model. The MM5 model allows for the integration of the hydrostatic as well as the non-hydrostatic equations of motion. The physics routines include many different choices for implicit treatment of convection, a mixed phase explicit treatment of cloudwater, rainwater, snow, and ice, and a choice of boundary layer parameterizations including the Blackadar PBL scheme as well as a second order Mellor-Yamada closure scheme. The mesh refinement scheme allows for an unlimited number of nests and nest-levels, which can translate and overlap. An example of a multi-scale nonhydrostatic application was given for an explosively deepening ocean storm case from ERICA. For this case, the resolution of the two-way interactive grids covered four levels (75, 25, 8.3, and 2.8 km). The successful simulation used two stationary domains (at 75 and 25 km resolution) and three translating

domains, which were moving with either a cold front (8.3 km resolution domain) or the center of the surface storm (8.3 and 2.8 km resolution domain). The model was able to capture the spin-up and overall structure of this event, as compared to satellite observations. The MM5 code is now being moved to a massively parallel system (the Intel) at Argonne, as well as to a cluster of IBM RS6000 workstations.

James Doyle showed results from a three-dimensional coupled ocean/atmosphere mesoscale prediction system (COAMPS). This model consists of nonhydrostatic atmospheric and hydrostatic ocean models, which can be integrated simultaneously. Idealized numerical simulations of Hurricane Gilbert demonstrate the capability of COAMPS to realistically simulate the mesoscale air-sea interaction processes. Mesoscale atmospheric structures such as spiral bands of convection and concentric eye walls developed in the simulations. In the coupled simulations, the intensity of the hurricane was hindered by strong cooling of the sea-surface temperatures forced by the the hurricane circulation. Other numerical simulations that were presented include a convective event and a case of marine atmospheric boundary boundary layer frontogenesis.

Su-Tzai Soong reported on a non-hydrostatic, fully compressible mesoscale atmospheric convection model which was developed to study heavy precipitation induced by the complex topography over southwestern Taiwan. The unique feature of this model is the adaptation of a third order advective scheme which preserves the peak values well and produces no phase error and little computational oscillations. The steep and complex topography over Taiwan can generate such oscillations, which if not dealt with properly, may either generate false clouds or cause computational instability. The scheme demonstrated no undesirable oscillation in a simulation of a thermal using a two-dimensional dry version of the model without applying any smoothing. The same model was used to simulate many intricate features of mountain waves without producing any ill effect. The complete two-dimensional model, including microphysical processes and radiation, was used to study the effect of complex topography in producing heavy precipitation in southwestern Taiwan produced by a rainband of the decaying typhoon Agnes, which passed the east coast of Taiwan three days before. The simulation clearly showed the formation of a storm over the mountain area and subsequent propagation of the storm to the southwestern plain caused by the continuous generation of new cloud cells at the western edge of the storm. The westward propagation of the storm combined with the eastward propagation of cells caused heavy precipitation and flood over the southwestern plain.

William Skamarock illustrated the use of adaptive grid refinement for a three-dimensional simulation of an intense squall line/MCS using the COMMAS model. A video of the simulation showed how the various sub-meshes were arranged automatically through an algorithm based on the location of the updraft maxima in the domain. This type of gridding strategy allows one to capture the details of convective evolution while also representing the environment in a credible way.

David Bacon introduced a novel approach for cloud/mesoscale modelling. The Operational Mesoscale Environment model with Grid Adaptivity (OMEGA) is a model built on a triangular prism mesh which is structured vertically, but is horizontally unstructured. The mesh is capable of continuous refinement so that OMEGA has variable horizontal grid resolution ranging from 100 km down to 1 km. A key feature of OMEGA is its inclusion of a wide variety of terrain, land/water, land use, and vegetation data. The other major advance of OMEGA, slated for the 1993-1994, will be the dynamic adaptation of the grid. By letting the grid resolve the regions of severe weather, OMEGA will achieve previously unachievable resolution in a mesoscale model.

Andrew Staniforth presented the principal attributes of a highly-efficient, variable-resolution, nonhydrostatic global model currently under development in Canada. This model is designed to be easily reconfigurable for multiscale applications ranging from the global all the way down to the meso-gamma scale. The numerical techniques include a finite-element spatial discretization (for variable resolution) on a rotated latitude/longitude mesh (to focus resolution anywhere over the globe), and a semi-implicit semi-Lagrangian time integration scheme (to avoid an overly- restrictive timestep limitation). Because the model is global, problems due to the imposition of lateral boundary conditions and their specification are avoided. Results from a shallow-water prototype were given to illustrate the potential flexibility of this approach to handle multiscale problems. A particularly interesting and surprising property of the horizontal mesh used is that fully 50% of the total number of meshpoints are contained within a 1/4 km uniform-resolution square sub-domain of length 100 km, yet the mesh is global in extent and each successive meshlength is only 10% larger than its preceding neighbor as one moves away from the high-resolution window. It was shown that a mesogamma-scale feature embedded in a synoptic flow can be successfully retained and forecast without deteriorating the steering synoptic and global-scale flow. If this behavior holds up for the three-dimensional model under development, then it was argued that it could prove to be a useful tool for multiscale research in the context of the CME.

Andrew Crook spoke on the problem of initializing cloud-scale models with single Doppler radar data. Two approaches to the problem were presented. In the first, which is mainly applicable to boundary layer flow, both components of the horizontal wind are determined by a tracking technique called TREC (Tracking Reflectivity Echoes by Correlation). The pressure and buoyancy can then be retrieved from a time history of the horizontal wind and application of the continuity equation to obtain the vertical wind component. Tests with this method on a number of gust front cases have shown that the motion of the front can be predicted with reasonable accuracy. The second approach to radar data initialization is the adjoint technique. The method attempts to find the initial conditions that produce a simulation which fits the available data in a least squares sense. The technique has been applied to single Doppler data of a gust front case from the Phoenix-II experiment. The horizontal velocity field has been retrieved to within 1.5 m s^{-1} rms error when compared with dual Doppler data.

Robert Wilhelmson spoke on tools currently available, as well as those planned for the next several years, for application to large-scale computational problems. Emphasis was placed on homogeneous computing environments across the spectrum of devices (mass storage. compute engines, visualization environments), and on increased resolution for visualization devices. No longer are supercomputers found only in government sponsored facilities such as NCAR, GFDL, and NWS. Today, there are many atmospheric scientists who use these new supercomputing facilities that are available to remote users over the Internet, a national network interconnecting hundreds of local and wide-area networks. This network has a cross-country backbone with network speeds between nodes at or above 1.5 megabits per second. This is more than 1,000 times greater than the 1,200 bits per second available during the early 80's. The next decade will be filled with new capabilities for researchers to carry out their investigations. For example, in the latter half of the decade a teraflop computer should be available. Computers that deliver this speed will most likely be highly parallel, with over 100 processors. Some of today's massively parallel machines already have over 1,000 processors. *The key to obtaining performance on these machines is the efficient use of these processors.* This has led to a growing interest in algorithms that can be used to achieve this high efficiency. Today's conventional gigaflop supercomputing will be handled in the near future by computers that can be purchased by a research group and placed in an office environment. If several of these computers are available, they can be interconnected through high speed links and simultaneously used to do a large calculation. Further, these computers can reside on high speed networks interconnecting supercomputers and personal computers. Larger memories will be coupled to increased computer speed, with maximum configurations well beyond the 32 billion byte memories

available today. In addition, the handling and storage of data will be expedited by larger disk farms, the use of new storage media, and higher speed access. DD-2 tapes, widely used in the professional video marketplace, can hold over 150 gigabytes of data (per tape), almost 1,000 times more than the archive tape in current use at many supercomputer sites.

Computers, their interconnections, and data storage systems are being referred to as a '*metacomputer*.' The metacomputer is a natural extension of parallel computers in which all processors are alike. Interconnections between different processors can reach over one gigabyte today and these speeds should increase significantly through the use of parallel channels over the decade. Within the metacomputer there will be facilities for making video tapes. High definition technologies will enable creation of these videos with substantially more resolution, at least as high as today's typical workstation monitors (approximately 1000 x 1000 pixel resolution). Sound will be integrated with visual images to provide another information dimension. Virtual reality environments will be used to transport the researcher into their computational space, experiencing three dimensionality and integrating their data based on this three dimensional stereo view. For example, it will be possible to walk under a growing storm and release air tracers or to fly through a storm checking for regions of high turbulence. The metacomputer is also an integrating concept for access to a wide variety of data needed to solve problems, often interdisciplinary in character, where small and large specialized data sets are stored at many sites throughout the country. Data management systems are needed by the researcher to check on what data is available and then to obtain portions of it over the national network. Further, the metacomputer will be used by groups or individuals around the country carrying out collaborative research. With new technological advances it will be possible for researchers at remote sites to collaborate as if they were in the same room, seeing the same computer screen, talking and pointing to what they see, using the computer as a blackboard, developing code together, and jointly controlling and monitoring simulations and data analysis. This will be important for tackling grand challenge problems such as the study of global change and the improvement in mesoscale weather forecasting.

Advances in computer technology and its use is being fostered through The Federal High Performance Computing and Communications (HPCC) Program. The strategic priorities of this program are to further U.S. leadership in HPCC, to increase industrial competitiveness through the use of HPCC technologies, and to accelerate the widespread application of these technologies for economic, national security, education, and global environmental purposes. The atmospheric science community is benefiting significantly from participating in these efforts, with new computational environments being explored.

Wilhelmson presented an example of a computational environment of the 90's called PATHFINDER (Probing ATmospHeric Flows in an INteractive and Distributed EnviRonment), a project at the National Center for Supercomputing Applications and NASA Goddard Space Flight Center. The mission of the PATHFINDER Project is to create a flexible, modular, and distributed environment for data handling, model simulations, data analysis, and presentation to be used in studying atmospheric and fluid flows, and which can be tailored for specific scientific research and weather forecasting needs.

4. Workshop proceedings and recommendations

Following the colloquium, the participants met in workshop breakout sessions to use the previous discussions as a base for discussions. The workshop session leaders were assigned five tasks by the meeting organizer to be completed before the end of the meeting:

- Assess the advantages and limitations of current modeling approaches being used in the topic area covered by that particular session
- Define the critical unknowns in the topic area
- Make specific suggestions for future modeling approaches, with emphasis on those activities which should be accomplished prior to the 1995 CME
- Determine the implications of these developments and approaches as they impact future observing system strategies
- Determine the observational requirements for coupled multiscale model validation

4.1 Joint sessions on initialization and data assimilation

Tom Warner and Fred Carr

a. Advantages and limitations of current approaches

Intermittent data assimilation

Concerning the characteristics of the intermittent four-dimensional assimilation approach first, the workshop made the following conclusions:

- The main *advantage* of this approach is that it is simple and uses primarily existing software (i.e., the model and objective analysis programs).

However, there are several *disadvantages* to this approach:

- There can be considerable model "shock" resulting from the inaccurate dynamic balance that results from the intermittent objective analyses.

- Associated with the dynamic imbalance is the lack of accurate mesoscale vertical motions resulting from each objective analysis; thus, a significant fraction of each forecast interval may be required in order for reasonable vertical motions to be generated internally by the model. As the assimilation window (model restart interval) is reduced, the model has less time to recover from the initialization shock and to spin up mesoscale structures such as vertical motion fields.

- The objective analysis of often primarily synoptic-scale data can remove mesoscale structures generated during the model forecast through local forcing, nonlinear interactions, etc.

- It is difficult to utilize "nonstandard" data that cannot be analyzed as point values of the predicted variables.

- The model initial state is not "optimal" in any sense.

Continuous data assimilation

Concerning the popular continuous data assimilation ("nudging") approach, the workshop concluded that the*advantages* of this approach are:

- The software is relatively simple to implement.

- It is economical to use relative to many of the next-generation variational procedures.

The *disadvantages* of this approach are somewhat similar in nature to those of the intermittent approach, namely:

- Model shock may result when the relaxation terms are shut off in data voids (in space and time).

- It is difficult to utilize "nonstandard" data such as rain rates and satellite cloud images.

- The model initial state is not "optimal" in any sense.

- Although the computational cost is much less than that of the next-generation variational procedures, continuous assimilation can become computationally costly if many data are available.

Physical initialization

The *primary advantage of* the physical initialization technique is that:

- The data utilized generally have mesoscale resolution (e.g., latent-heating rates based on radar-reflectivity), and thus their use can reduce, or at least not inhibit, model spinup time.

The *disadvantages* of this approach are:

- It is often difficult to quantitatively interpret the data used in this approach because they are based on indirect measurement systems (e.g., radars and satellite sensors).

- This approach is often model specific because it is sometimes closely tied to physical-process parameterizations.

Variational approaches

The *advantages* of the variational approach are:

- Observations of both "traditional" (u,v,T) and "non traditional" (e.g. - radiances, reflectivity) variables can be incorporated into the assimilation.

- The cost function can include observations, background fields (usually prior forecasts), as well as additional dynamical and/or smoothness constraints to accomplish the desired goals of the analysis.

- The technique is adaptable for any type of model and scale; if the model equations/physics are appropriate for a particular phenomena and the data are "sufficient," then an optimal solution can be found.

The *disadvantages and unresolved issues* with respect to variational techniques also represent the critical areas for research:

- *Discontinuous processes*: The treatment of switch on/off physics such as cumulus parameterization causes difficulty in the minimization; this is an active area of research and some promising solutions have already been identified.

- *Computational expense*: Ten or more iterations of forecast and adjoint models over the assimilation period are usually required. The use of preconditioning, lower-resolution models, simpler models/adjoints during assimilation, better minimization algorithms and faster computers may all contribute to the solution of this problem. The key operational issue is whether the extra effort and expense of this approach is worth the benefit it may provide to the subsequent forecast.

- *Model error*: The model is usually assumed perfect when in fact it has error (which may be considerable if the model physics can't simulate phenomena which are present in the data). In addition to improving the model, possible solutions include adding a model bias correction term, or making use of the Kalman filter technique, in which the model error is known at all times.

- *Error statistics*: The observational and background error covariance statistics (as well as the weights to be assigned to the various additional constraints as a function of space and time) are important to the quality of the analysis and need to be better simulated. For mesoscale and convective scale flows, the statistics are not known at all and are probably non-Gaussian. Much effort is required to successfully address these issues.

Cloud model initialization

The *advantages* of this exploratory technique include:

- Modified forward insertion and dynamic relaxation techniques have shown some success if thermodynamic retrieval methods and/or other dynamical constraints are incorporated.

- Multi-parameter radar data can be used in the initialization of hydrometeors and other cloud microphysical parameters.

The present *limitations* of this technique consist of the following problems:

- Simple insertion or nudging of wind data will not recover the correct temperature field.

- If data from only one Doppler radar is available, then single-Doppler retrieval methods need to be applied. Velocity azimuth display and related methods just provide a vertical sounding of the horizontal wind for a volume around the radar. TREC techniques apparently are restricted to clear-air boundary layer applications.

b. Critical issues

The unresolved issues and challenges in the areas of ***current and next-generation data assimilation*** include:

- "Optimal" nudging approaches that employ variational techniques to define relaxation coefficients need to be further developed and tested to determine their usefulness.

- The procedure needs to be further tested with mesoalpha- and mesobeta-scale models

- Specific critical issues for variational techniques were listed immediately above. The key issue can be summarized as: Even if solutions are found for most of the current problems, will the extra effort and expense of the variational methods be repaid by a significant improvement in the assimilated state and resulting forecasts?

- It is necessary to determine how relaxation coefficients can be specified in such a way that information about short-time-scale processes can be introduced without the Newtonian terms dominating the solution determined by the model dynamics.

- Concerning physical initialization, the quality and interpretation of indirectly measured precipitation data need to be improved, in conjunction with the development of techniques to retrieve cloud water, cloud ice, and other hydrometeors.

- Precipitation and hydrometeor estimates from the national network of WSR-88D radars need to be incorporated into physical initialization procedures.

- The proper vertical distribution of specified heating and moistening rates for different mesoscale phenomena needs to be determined. The role and importance of cloud microphysical processes in this problem also needs to be studied.

- Techniques need to be developed to insert information about fluxes, transports, and other process rates (e.g., evapotranspiration, rainfall rates, and TOA radiative fluxes) into analyses in a consistent fashion into coupled models.

- Another issue is how adjoint and other variational techniques can be used in coupled models such as coupled hydrological/atmospheric models.

- Little is understood about how shortcomings in model physical parameterizations and numerics affect four-dimensional data assimilalation fields.

- One of the major suggestions of this workshop is the need to develop techniques to adapt present data assimilation approaches to multiply-nested or adaptive grids.

The primary problems, issues, and research ideas ***concerning convective-scale model initialization*** which arose from the discussions in this workshop breakout session concern data types and frequency, adjoint techniques, boundary conditions, data gaps, and initialization of microphysical processes:

- *Many questions remain on the types of data needed, the spatial density and temporal frequency required and the amount of error the techniques will tolerate.* The data frequency issue is especially critical because model time steps for cloud models are much smaller than the radar volume scan interval plus the data often have to be smoothed to reduce noise in the time tendencies; thus the assimilation window may be too large for rapidly evolving phenomena. Although retrieval techniques using wind data alone have shown some success, the presence of observed temperature data helps significantly. Knowledge of the water vapor, liquid, ice and hydrometeor fields is crucial for thunderstorm prediction. Many more real-data experiments to explore these and other issues are needed.

- Although they have shown success in the retrieval/analysis problem, *much work remains to incorporate adjoint methods into a data assimilation system for real time prediction of storm-scale flows.* All the problems listed for variational techniques above apply; the issue of discontinuous processes is even more acute here. In addition, the lack of predictability of the model for observed convective phenomena may lead to multi-minima in the cost function.

- The need for accurate boundary condition information is crucial for analysis and forecasting over small regional domains. *The treatment of boundary values in the adjoint approaches is especially important.*

- Problems exist for *specifying the initial conditions in regions where no data are available*; e.g. in the clear air environment surrounding a convective storm.

- Studies on the use of multi-parameter radar to accomplish the *initialization of microphysical processes* should be continued.

c. *Observational requirements for improved data assimilation systems*

Knowledge of the three-dimensional mesoscale structure of the moisture field at frequent time intervals is the most crucial advance needed. No existing observing system is capable of satisfying this requirement. The strengths of many individual systems need to be combined to overcome the current deficiencies in moisture data measurement. Important components include:

- Combined visible, infrared, and microwave channel data from satellites to infer water vapor distribution, precipitable water, cloud coverage and precipitation estimates, and cloud water, ice and hydrometeor information.

- Ground-based remote sensing techniques for moisture, especially the promising DIAL system.

- WSR-88D reflectivity data to infer surface precipitation rates as well as cloud water/ice distribution. Dual polarization and/or multi-parameter radars should be utilized to improve information on hydrometeor content and other cloud microphysical parameters.

- In situ data from conventional radiosonde measurements is very important, not only for their detailed vertical profiles of moisture but for calibration and assessment of the remote sensors.

- The CASH component of the ACARS system should be strongly encouraged; high-frequency measurements during takeoffs and landings are especially desired.

- High-resolution surface moisture measurements are important for the convective initiation problem.

- Research aircraft data will be needed in clouds to measure cloud microphysical parameters; these data are needed to initialize cloud models as well as to assess the accuracy of retrieval techniques used to deduce moisture variables from Doppler radar data.

Other important observation needs for data assimilation are:

- Co-location of frequent rawinsonde releases near remote-based sounding systems is recommended so that the relative accuracy of their velocity and temperature measurements can be assessed. Use of CLASS and mobile CLASS systems is desired. Access to the raw sounding data is requested to maximize use of the vertical detail present in the data.

- High-density raingauge networks are needed to help calibrate WSR-88D precipitation algorithms at each site. Both the gauge and radar precipitation estimates should be available to operational centers at hourly intervals.

- Soil moisture, snow cover, albedo, and other surface characteristics need to be measured to allow testing of their incorporation into data assimilation schemes. Measurements of surface fluxes are needed for verification of model estimates.

- The ACARS program should be expanded to include more aircraft and greater frequency of measurement.

- All WSR-88D radars in the CME should have recorders, not just the ones operated by NOAA.

- In order for data assimilators to make proper use of the data, the data from each observing system should be accompanied by complete documentation on the system's operating principles, measurement strategy, and accuracy, as well as on the quality control procedures used in processing the data.

- Observing system simulation experiments for future observing systems (alone and in combination with others) should be conducted to help determine what data types, accuracy, density and distribution are most important to analysis and forecast systems; this will help determine priorities for selecting which systems to design and implement in future field experiments.

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4.2 Joint sessions on moisture processes and cumulus parameterization

4.2.1 Session on measurement/modeling of moisture processes

William Cotton

The specific recommendations of the workshop session on the measurement and modeling of moist processes are as follows:

- *MCS measurement strategies must extend well beyond the "visible" cloud boundaries.* All the important sources and sinks of moisture associated with MCS genesis and evolution (e.g., large-scale advection, evapotranspiration, precipitation) must be identified in three dimensions and with sufficient temporal resolution to be useful for developing, improving, and verifying boundary layer, radiation, and convective parameterizations.

- *Do not limit observation of MCSs to their dynamically active stages, but include measurements of "fossil" MCS residue.* Middle and upper tropospheric moisture and cloud formation are examples of MCS "fossil" effects which can have profound upscale feedback effects.

- Use the "best" soil hydrology model and its adjoint to "retrieve" soil moisture and vegetation parameters.

- *Design "plug"-compatible routines.* Cumulus parameterization, microphysics, radiation, and turbulence schemes should all be made easier to implement and test, including documentation for general use prior to CME. Community access to "radiation" codes should be provided.

- Couple aerosol and cloud microphysics models, and obtain measurements of aerosols and hydrometeor spectra for radiation calculations.

- *Provide soundings over the eastern Pacific* to identify sub-tropical jets and jet streaks entering the southwest and impacting the MCS genesis region. Some suggested approaches to obtaining these measurements include: use of remotely piloted vehicles equipped with automated (i.e., jukebox units) dropsonde systems, and expanding the ACARS systems to include automated dropsonde units on a few overseas commercial aircraft.

- *Integrate satellite, surface (e.g., ASOS ceilometer), and radiosonde data to provide an observational analysis of atmospheric moisture with mesoscale resolution.* This is urgently needed for further development and validation of coupled multiscale models.

- *Hydrological cycle improvements are needed in models.* Improvements are critically needed to not only produce accurate precipitation in all kinds of situations (both strongly forced and quasi-barotropic), but also to transport moisture vertically to produce clouds in a physically consistent manner. Furthermore, the model treatments of clouds as they relate to the radiative budgets, which typically rely upon arbitrary and crude statistical relationships between cloud coverage and relative humidity, need to be greatly improved by using explicit prediction of condensate fields and knowledge in the initial state of the models of the cloud bases, cloud tops, and optical properties.

- *A critical need exists to understand the moisture cycling properties of MCSs and the dynamic/thermodynamic processes that control their evolution.*

4.2.2 Session on cumulus parameterization

Bill Frank

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Regarding the cumulus parameterization issues, ten major issues were raised that were suggested to be critical unknowns requiring immediate attention:

- Should convection be handled explicitly, implicitly, or both ways in models with grid meshes of 2-20 km? *It is essential to acquire a data base adequate for verification of cumulus parameterization assumptions and for development of new approaches.* This will require very high temporal resolution data over multiple scales to analyze complex interactions between clouds and the mass field. It will also require in-situ measurements of thermodynamic properties and hydrometeors.

- *What closure assumptions are valid when the model grid scale is 50 km or less?* Better means of comparing parameterizations and their component parts and assumptions need to be developed. Superficially, it would appear that cumulus parameterizations should just be black box subroutines that could be installed and tested against each other in any number of models. In practice, this doesn't work. Existing parameterizations tend to interface with many parts of their host models at several stages of the simulation. Some are greatly influenced by the initialization scheme, some are highly sensitive to vertical resolution or other physical packages in the model. Further, the schemes are complex, and it is extremely difficult to evaluate why one scheme behaves differently from another in a model run. One scheme might have a trigger function that is slightly better than another's in one particular situation, thereby producing a much better forecast, even though the losing scheme may contain a much more realistic closure or cloud model. Rather than direct tests between existing parameterizations, what is needed is to isolate the major assumptions used in each scheme and test these assumptions within carefully controlled experiments in which all other components of the scheme are similar.

- *There is a need for further research on the fundamental links between convection and the mesoscale circulations within which most deep convection occurs.* We need to find out how individual clouds interact and exchange mass and hydrometeors with their immediate surroundings. The sensitivity of simulations to different rates of net diabatic heat release and to its vertical distribution needs to be documented. Effects of the moisture field on convection and vice-versa need to be better understood. Further research is needed to develop cumulus parameterization approaches that predict convection in terms of the physical processes that directly cause clouds to form.

- Both shallow and deep convective clouds should be predicted with the same scheme, using similar physical assumptions.

- Efforts should be made to integrate implicit and explicit cloud parameterizations, as well as with radiation, turbulence and boundary layer schemes.

- *Momentum transport processes need to be accounted for.* Simple momentum mixing schemes (so-called cumulus friction) are not sufficient to account for the total momentum flux that occurs in an MCS. Development of momentum-exchange parameterization techniques is badly needed, particularly for climate models and other coarse-grid models.

- *The importance and effects of slantwise convection in MCS studies should be estimated.* Slantwise convection is important and often occurs in regimes where upright convection is less prevalent. In models with relatively fine grid meshes it may be possible to resolve these phenomena explicitly, though this would require high vertical resolution. Without sufficient

resolution the model will tend to alias the slantwise convection to whatever shape it can resolve and may disassociate heat and momentum transports in a physically incorrect fashion. Further research is required in this area.

- *The most critical process that needs to be determined to improve cumulus parameterizations is the rapid interaction between the clouds and the mass field on meso-beta through synoptic scales.* Since the temperature perturbations associated with even the most intense deep convection are extremely small except at cloud top and in the boundary layer, the best way to infer these interactions is by observing the divergent component of the winds. While a dense large-scale rawinsonde network helps document the evolution of the wind field, temporal resolution is always insufficient to fully document rapid evolution of the divergent flow. It should be possible to use wind profilers to interpolate in time between rawinsonde sampling times to diagnose the interactions between convection and the mass field on large scales to a much greater degree than has been done previously. Specific modes of atmospheric response to convection can be documented, as well as changes in the large- scale divergence that precede changes in convection.

- *It is also important to document the detailed structure of the atmosphere on very small scales.* Despite a great deal of research on convection over the last several decades, there is still a considerable uncertainty about how convective updrafts interact with their immediate surroundings. Deep convection tends to be embedded within meso-beta-scale circulations that are often saturated and contain hydrometeors. *High temporal and spatial resolution measurements of the three- dimensional atmospheric winds on the scale of 2-20 km need to be obtained.* Doppler radar appears to be a logical system with which to make such measurements. These need to be augmented with in-situ measurements of hydrometeors and thermodynamic parameters from aircraft, coupled with a high-resolution surface network to determine boundary layer structure and rainfall patterns. Observations of convective draft structure need to be determined from a combination of in-situ and airborne Doppler radar observations.

In summary, convection is much more of a multi-scale phenomenon than is commonly realized; experiments that have focused only on the structure of individual clouds or MCSs have not been able to resolve the nature of the processes that cause convection or to document the complete effects of convection upon larger scales. There have been a number of valuable field experiments during the past few decades that have documented many features of deep convection and MCS structure. However, none of these experiments have had adequate time and space resolution of the surrounding regions, up to the synoptic scale, to allow accurate determination of the interactions between convective systems and the large-scale flow. Cumulus parameterization schemes currently assume various types of equilibrium between the convection and the grid- scale flow that are clearly ill-posed on the scales of mesoscale model grids. It is crucial that a better set of observations be obtained to design better parameterization approaches and to allow proper verification of parameterization assumptions.

N94-24395

4.3 Session on coupled land surface/hydrological/atmospheric models

Roger Pielke

a. Assessment of current abilities and approaches

The current model capabilities in the context of land surface interactions with the atmosphere include only one-dimensional characterizations of vegetation and soil surface heat, moisture, momentum, and selected other trace gas fluxes (e.g., CO_2) The influence of spatially coherent fluxes that result from landscape heterogeneity have not been included.

Valuable representations of several aspects of the landscape pattern currently exist. These include digital elevation data and measures of the leaf area index (i.e., NDVI from AVHRR data). A major deficiency, however, is the lack of an ability to sample spatially representative shallow and (especially) deep soil moisture. Numerous mesoscale modeling and observational studies have demonstrated the sensitivity of planetary boundary layer structure and deep convection to the magnitude of the surface moisture flux.

b. Most critical unknowns

The unknowns include specific meteorological parameters as well as physical processes. The unknown physical processes include the following:

- What is the role of subsurface hydrology (vertical and horizontal transport) in determining surface heat and moisture fluxes?
- How important are biospheric/chemical processes in affecting surface fluxes?
- How does the boundary layer modulate the interactions of the surface with clouds?
- How have human influences on land use altered convection and the hydrologic cycle (this question is also important as a linkage to global change)?
- What are the nature and causes of temporal and spatial variability of rainfall?
- How do surface characteristics affect "predictability"?
- What scale of surface data is the most critical to develop the surface forced mesoscale circulations which may help trigger MCS's? The critical scale may help us determine how fine our surface data must be for future operational and research needs. Is there a scale beyond which there is little mesoscale return?
- How do PBL dynamics and structure affect this critical land-surface data scale?

The CME needs to consider the following in defining measurement requirements:

- Borrow heavily from FIFE and BOREAS experiment plans.
- Required for scaling up ("aggregating") from the land surface to the MCS scale: latent heat, sensible heat and net radiative fluxes are needed at enough sites to characterize means and variability.
- Incorporate satellite remote sensing technologies, especially the FIRE results, into the CME project design and operation to support model initialization/validation.
- Start with high-resolution observing system simulation experiments (OSSE) then gradually degrade the resolution of the simulated data to examine sensitivity to the quality, distribution, and sampling of various land surface and vegetation parameters.
- The importance of high-resolution measurements near surface landscape boundaries needs further exploration.

The needed spatial and temporal resolution of these data need to be determined using existing observational and modeling studies. The evidence available at present suggests that averaged values of land surface parameters over (1 km)^2 footprint areas may be sufficient.

c. Recommendations for the improvement of coupled multiscale models

There is a need to permit two-way interactions between the atmosphere, and biophysical and hydrologic processes. This feedback is essential in order to properly represent the control on transpiration of water into the boundary layer environment. In addition, since stomatal conductance of water is directly related to carbon dioxide fluxes, these models must also influence dry deposition of other chemical species, particularly hydroscopic aerosols and gases. These interactions point to the necessity for interdisciplinary activities in the CME. Involvement by the hydrology community would be mutually beneficial. The meteorological models require knowledge of soil hydraulic properties for input to surface layer parameterizations. Correspondingly, an accurate characterization of precipitation, evapotranspiration, and landscape structure is necessary for input to hydrology models. A similar relationship exists with the ecological modeling community. Atmospheric models are strongly affected by vegetation processes, while the ecological community needs atmospheric information to properly simulate soil and vegetation biophysics (e.g., the soil carbon budget).

Specific improvements for coupled multiscale models include:

- Continue work to minimize further the reflection and refraction of wave energy as it is transmitted through the lateral boundaries of meteorological nested grids.

- Develop physically and computationally consistent treatment of cumulus convection and boundary layer turbulence in nested grid models.
- Introduce procedures to aggregate subgrid terrain and landscape variations into the variable grid increment sizes that exist in nested multi-scale models.
- Apply techniques to assimilate synoptic and asynoptic observational data on nested grid domains.
- The value of adaptive multiscale models as contrasted with a nested grid modelling framework needs to be quantitatively investigated.
- The theoretical time limits of predictability as a function of spatial scale needs to be investigated using sets of coupled multi-scale model simulations.
- The level of physical completeness in hydrologic and ecological models, which are to be coupled to atmospheric models, needs to be described. A critical question is the level of detail needed in these models so as to accurately represent the meteorological response.
- The required accuracy in the simulation of winds, turbulence, and radiative fluxes for use in atmospheric chemistry models needs to be defined. Since these chemical models require concentration fields, it is essential that the differential advection and diffusion of chemical species be correctly represented.

d. Observations needed to initialize and verify these models

Specific measurements that we need include the following:

- Vegetation cover, soil characteristics, terrain slope on scales <1 km
- Recording/archiving of *all* WSR-88D data: e.g., base scan reflectivity (for rainfall rate validation), gate-to-gate velocity/reflectivity (morphology of storm)
- Soil moisture profiles by neutron probe (needs to be automated)
- Dual ground based Doppler lidar to characterize boundaries (dryline, irrigated areas)
- Ground based radiometric profilers with RASS
- Mobile CLASS soundings
- Aircraft: King-Air class for PBL; NASA downward-looking DIAL lidar (especially near boundaries); Eldora-2; and NOAA P-3 airborne doppler
- New types of measurement platforms (e.g., new types of measurement platforms for economical boundary layer measurements such as instrumented radio-controlled aircraft)
- Data archival and distribution (CD-ROM? Distributed archive?)

The specific data needed to characterize the landscape structure include AVHRR NDVI data at 1 km pixel scales for at least a weekly sampling period, digital elevation data sampling scales of ~50 m, and use of microwave data to estimate antecedent rainfall. The

CME planning committee should incorporate satellite remote sensing technologies, especially FIFE results, into the project design and operation. Existing observational opportunities should be exploited, such as WSR-88D, the Oklahoma mesonet, and the profiler network. In addition, CME should establish a linkage with other programs (ARM-CART, GCIP, USWRP, etc.) and disciplines (hydrology, chemistry, ecology), and also leverage existing technologies and data sources (EROS, etc.).

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4.4 Joint sessions on modeling of boundary layer and radiative transfer processes

4.4.1 Session on modeling of boundary layer processes

Chin-Hoh Moeng

The following topics were addressed in the PBL session of the Workshop: (1) current PBL parameterizations used in mesoscale models, (2) critical issues in improving PBL parameterizations for mesoscale models, (3) suggestions for future modeling efforts, and (4) suggestions for observing system strategies.

a. Current PBL Parameterizations Used in Atmospheric Models

Current general circulation and mesoscale models employ either a bulk or multi-layer PBL scheme. The former includes mixed-layer modeling while the latter encompasses Richardson number-dependent K models, Mellor--Yamada one-equation models, transilient theory, and the Blackadar model. A common advantage of all parameterizations is that they are simple and computationally economical for mesoscale and climate models. The shortcomings of these models are the following:

- These models were developed for horizontally homogeneous PBL flows. They also were meant to account solely for turbulent fluxes (because the closures in the models were determined based on turbulent flows and turbulence theories)
- Some of the models, viz., mixed-layer and Blackadar models, are appropriate for convective PBLs only
- Interactions between cumulus clouds and the PBL are absent in most models
- PBL stratus-type clouds are usually neglected

b. Critical Issues for Improving PBL Parameterizations for Mesoscale Models

We have identified three critical issues in developing improved PBL parameterizations.

- *First, how should inhomogeneous surface features be incorporated into PBL schemes?* All current PBL models were designed and built for statistically horizontally-homogeneous PBLs. However, in mesoscale environments, PBLs are often horizontally inhomogeneous owing to heterogeneous land surfaces, the presence of cumulus clouds, and problems near fronts. Heterogeneous surface conditions, such as land-sea contrasts and nonuniform terrain, can strongly affect many mesoscale systems. Thus, PBL parameterizations must be able to account for these surface effects if they are to be successfully used in mesoscale systems.

- *The second issue concerns how cumulus-induced subgrid-scale effects should be included.* Clouds in mesoscale systems strongly modify the underlying PBL structures. For example, cumulus downdrafts bring cooler and drier into the PBL, cumulus-induced subsidence in the environment suppresses the PBL growth, cloud cover modifies radiation inputs into the PBL, and rain evaporation cools the PBL. Often, these modifications change the subsequent mesoscale system development. It is therefore important to incorporate these modifications into PBL parameterizations.

- *The third issue concerns how to incorporate the formation and dissipation of PBL stratiform clouds in models.* Many frontal storms are preceded by low-level PBL stratiform clouds, but it is not clear how these clouds affect storm development. Often too thin to be resolved in the vertical grid, these stratiform clouds need to be included in the PBL parameterization.

c. *Suggestions for Future Modeling Efforts*

- *A working group should be formed to evaluate and develop PBL models in the mesoscale context.* Group tasks would include, first, surveying and reviewing the currently-used PBL models; second, designing a comprehensive database (through both large-eddy simulations and field measurements); third, systematically evaluating the model performance against the database; and finally, developing better schemes. This evaluation exercise would also provide users with both an assessment on the adequacy of PBL model vertical resolution, and information on the limitations of each type of PBL model that would help in interpreting model results. We may also want to apply this evaluation process to coupled land process-PBL models, coupled cumulus parameterization-PBL models, and coupled air chemistry-PBL models. This will depend partially on whether a good database for such evaluation can be identified.

- *Include unresolved mesoscale fluxes in multiscale models.* In mesoscale modeling, some parts of the mesoscale circulations are subgrid-scale motions that coexist with turbulent motions. Roger Pielke, using a mesoscale model, showed that the heterogeneous-surface-induced mesoscale motions could generate fluxes that are comparable to and/or larger than the turbulent fluxes in windless environments. We propose more studies in this direction in order to develop a PBL parameterization to incorporate these combined fluxes. This may require more observational data and the use of large-eddy simulations with a numerical domain large enough to cover some mesoscale circulations.

- *Use cloud-resolving models to study PBL-cumulus interactions.* Most current PBL models do not consider PBL-cumulus interactions, which may be crucial for convective storm development. Cumulus circulations extending into the PBL (downdrafts and cloud roots) also produce non-turbulent fluxes that are not included in PBL models. We propose to use a cloud-resolving model with a comprehensive PBL parameterization (or, if possible, a nested LES model) to study and subsequently develop parameterizations to incorporate these interactions, both in quiescent and more disturbed (e.g., frontal or topographically-forced) cases.

- *Improve PBL models to accurately represent stable PBLs.* Many convective storm systems develop at night. However, current PBL models are unable to accurately represent the stable PBL. For example, models underpredict the height to which surface cooling reaches, due to the fact that stable PBL structures are strongly affected by gravity waves, terrain-induced drainage, longwave radiative cooling, and turbulence intermittency---all of which are not considered in current PBL models. We propose to use a nested-grid large-eddy simulation method to better understand stable PBLs.

- *Study PBL stratus clouds and their effects on mesoscale systems.* PBL stratus-type clouds play an important role in the climate-radiation budget. They may also be important for the development of mesoscale frontal system circulations, as discussed by Steve Koch (Session 3.4). A stratus-topped PBL is much more complicated and less understood than clear PBLs, because its structure is strongly affected by many additional physical processes (e.g., longwave and solar radiation, condensation and evaporation, and drizzle). How the stratus-topped PBL grows (i.e., its entrainment rate) is still not understood. We propose using large-eddy simulations, together with observations, to study PBL stratus clouds and their role in mesoscale development.

d. Suggestions for Observing System Strategies

Coordinated efforts between modeling and observation should be strengthened in order to meet the many scientific challenges we have identified in this Colloquium. The following are some specific suggestions for PBL studies.

- In order to better understand (and subsequently parameterize) the underlying PBL effects on a mesoscale convection system, we need to learn first how the PBL structure (e.g., height, flux profiles, etc.) evolves along with the overlying convection and how it varies spatially within the system. For this purpose, *we need to design field experiments that can simultaneously measure the PBL and the overlying convection.* This may require using aircraft, acoustic sounders, wind profilers, lidars, and radars simultaneously. So far, several experiments (e.g., FIFE) have been carried out to study the inhomogeneous surface effects on weather and climate. Others (e.g., CINDE and CaPE) have collected data on convection initiation. Before the Cooperative Multiscale Experiment takes place, we need to gather information on what those experiments have and have not learned in this area.

- To study the stable PBL and its effects on storm development, we need to combine observations with certain PBL modeling that can isolate the effects of gravity waves, cold-air drainage, longwave radiative cooling, and intermittent turbulence. For example, a PBL model combined with a linear gravity wave model may be used to study the gravity wave effect, while a nested-grid large-eddy simulation code can be used to study turbulence intermittency, in the context of observational studies.

- We also need to learn more about the types of convective storms that are preceded and strongly affected by PBL stratus clouds. Marine PBL stratus clouds were observed extensively during the FIRE field experiment. We need to observe continental PBL stratus clouds and their interaction with mesoscale systems.

- *We further recommend the use of chemical species as tracers in observing the transport properties of PBL turbulence and clouds.* Different chemical species have different sources and sinks. Most species do not affect mesoscale, cloud-scale, or turbulence dynamics. They can be useful, therefore, in studying and isolating different transport processes (e.g., top-down and bottom-up diffusion).

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4.4.2 Session on modeling of radiative transfer processes

Piotr Flatau

a. Current status of modeling needs

Six critical issues surfaced in the discussion concerning scale-interactive radiative processes relevant to MCSs, namely the needs to:

- Expand basic knowledge of how MCSs influence climate through extensive cloud shields and increased humidity in the upper troposphere.
- Improve radiation parameterizations used in mesoscale and GCM models.
- Improve our basic understanding of the influence of radiation on MCS dynamics due to diabatic heating, production of condensate, and vertical and horizontal heat fluxes.
- Quantify our understanding of radiative impacts of MCSs on the surface and free atmosphere energy budgets.
- Quantify and identify radiative and microphysical processes important in the evolution of MCSs.
- Improve the capability to remotely sense MCS radiative properties from space and ground-based systems.

One emphasis of these six critical issues is clearly on global climate through MCS-generated "cirrus" clouds; "cirrus" here is used in the broad sense including optically thin or thick stratified upper level clouds. Thus, the FIRE I and II Cirrus projects (Starr 1990; see also special issue of *Monthly Weather Review*, November 1990) and ARM objectives are relevant. For this reason we suggest to *collaborate with the FIRE and ARM communities*. This is also why research on "dissipative" stages of MCSs is strongly emphasized here. It is quite challenging because there is a natural tendency to study "weather" but not weak systems. The other new and challenging issue related to the dissipative MCS stage is the development of non-local GCM parameterization of cirrus and related cloud radiative forcing. In that way CME will complement the "local" strategy of an ARM CART site.

b. Most critical unknowns

Our present approaches to the MCS radiation problem are inadequate for the following reasons:

- There is no emphasis on climate issues; long-term mesoscale model integrations and the study of the dissipative stage of MCSs are needed.

- Our knowledge of the optical properties of clouds related to MCSs is incomplete.
- Very importantly, no consistent radiation-microphysical coupling exists in current mesoscale radiative transfer schemes.

c. Specific recommendations

The recommended activities by this group consist of the needs to:

- Develop and validate a community radiative transfer code suitable for use with mesoscale models, and establish an intercomparison project to isolate and understand radiative processes in mesoscale models.
- Encourage work on the sensitivity of long-term mesoscale model integrations to changes in radiative transfer parameterizations.
- Assess which measurement strategies are needed for remote active and passive sensors, radiometers, and microphysics probes.
- Develop field strategies to study climatic influence of MCSs; these may include long level flight legs in stratiform region "debris" downwind of dissipative stage of MCS (in contrast to step legs in the region of active MCS), and measurements of upper level humidity increase due to MCSs.

d. Implications for observing system strategies

The foregoing concerns indicate the need for these observational approaches:

- Measure moisture, cloud cover, microphysical properties on large spatial and temporal scales. Combine in situ, active and passive remote sensors, and satellite data.
- Determine MCS related cloud optical properties such as optical thickness, their morphology, and microphysical composition.
- Provide observations to establish the radiative budgets of different kinds of MCSs throughout their entire life cycle.
- Collaborate with other radiation field campaigns and projects.

N94-24398

4.5 Session on coupled atmospheric/chemistry coupled models

Anne Thompson

a. Current model limitations

- *Current coupled regional meteorological/chemical models have fairly crude parameterizations of surface and boundary layer processes.* For example, deposition of trace gases to the surface and emission of other species from the soil and from vegetation need to be better specified in the models. One of the most critical boundary layer meteorological parameters is the depth of the mixed layer. The simulated diurnal variation of this depth needs to better follow observations.

- *Parameterizations of convective clouds also need to be more realistic.* Convective clouds on all scales from small fair-weather cumulus to well organized MCSs need to be considered. Upward transport of trace gases is typically simulated, but downward motions within the cloud are not always considered. Very little data are available to validate schemes developed to simulate boundary layer venting by non precipitating cumulus clouds.

- Other limitations of current models include radiative effects, heterogeneous chemistry, and production of NO_x by lightning. Production of aerosol has generally been neglected in regional models. Cloud microphysical schemes and treatment of radiational characteristics within and surrounding a cloud remain the largest uncertainties of cloud-scale models. When photochemical models are run in conjunction with cloud models, there are large uncertainties in the photolysis rates within and above the cloud. *These models are limited by a lack of observational data to verify convective transport of ozone precursor gases and subsequent ozone production..*

b. Current issues and critical unknowns

The most crucial scientific issues and problems that this workshop defined are these:

- *Obtain field validation of model-predicted cloud dynamics.* Model simulations reveal very complex dynamics for which almost no observational verification exists. Fortunately, several trace gases of interest to chemists are also excellent tracers of cloud dynamics.

- *Determine the role of convection in stratosphere-troposphere exchange.* Upward and downward motions affect O_3, NO_x, and other trace gases.

- *Verify ozone production enhancement following convective transport of precursors* shown by tandem cumulus/chemical modeling approach. In particular, confirmation of the predicted magnitudes of cloud outflow and downstream photochemical ozone production is needed in a concerted chemical-mesoscale field program. The magnitude of these processes must be determined on a global scale; this requires better parameterizations of convection and chemical reactions.

- Determine the role of cloud microphysical processes in chemical scavenging and the role of lightning in NO formation.

- Further work is needed on the role of heterogeneous processes in altering ozone and sulfate production in clouds; NO is a key trace gas in the troposphere and lower stratosphere.

c. Modeling Activity to be Completed Prior to the CME

Some model improvements are currently underway. For example, the transilient matrix method of parameterizing convective transport of trace gases in a regional model has been tested in a version of RADM (Walcek 1993). A Regional Particulate Model, based on RADM, is being developed at EPA to simulate the production and transport of sulfate aerosol. The GCEM has recently been improved with a new cloud microphysics scheme, and transport of trace gases using GCEM winds has been improved with a new numerical advection scheme. Hydrometeor data from GCEM will be used to better estimate heterogeneous losses of trace gases in the Goddard 1-D photochemical model. All of these

activities will likely be completed before the CME is conducted. However, the CME will provide data that will be useful in validating these new model formulations. The experiment (data collection strategies described in the next section) will stimulate further model improvements, particularly addressing the limitations listed above. Of great importance with respect to the CME will be the planned linkage between the GCEM and the NCAR/Penn State mesoscale model.

d. Specific recommendations and experimental strategies

Multiscale surface layer - PBL - chemical flux measurements

Surface hydrology and meteorology field studies in CME should be supplemented with chemical flux measurements to enhance the data base for deposition and emissions for use in regional modeling. Fluxes of CO_2, O_3, NO_x, and NO_y should be measured in conjunction with fluxes of sensible heat, latent heat, soil heat, as well as albedo and vegetation characteristics. Profiles of these species should be measured simultaneously with those of temperature, humidity, and winds. Scale issues should be addressed over heterogeneous land use and terrain. For example, measurements should be made to determine how point source fluxes of trace species aggregate to form a grid cell size emission. The importance of subgrid fluxes due to subgrid circulations over regions of heterogeneous land use should also be assessed.

Eulerian budget study

Parameterizations of cloud-scale processes are usually based on a number of empirical observations or conceptual models of the nature of cumulus convection, and there is an ongoing need to validate and reaffirm the accuracy of these models with observations. Over the past 20 years, meteorologists have evaluated cumulus parameterizations using measurements of heat, moisture, and momentum. By carefully measuring the time rate of change of potential temperature, water vapor, or momentum, and also monitoring the inflow, outflow (and wet deposition) of these variables, it is possible to "measure" the integrated effects of cumulus clouds on the budgets of these parameters within an isolated atmospheric column containing clouds. These meteorological tracers (heat and moisture) undergo both convective transport and diabatic effects as they are acted upon by an ensemble of cumulus clouds, and as a result, it is often difficult to directly distinguish these two effects.

Using measurements of chemical species concentrations as passive tracers in the vicinity of convective storms, it is possible to directly assess the dynamic exchange of air within an atmospheric column. Carbon monoxide (CO) and ozone (O_3) are two chemical tracers that do not undergo physical or chemical transformations on the time scale of convective processes, and therefore can be used as a complement to the existing meteorological tracers. *We recommend that CO and ozone be measured* in the same manner that temperature and moisture have been measured in past meteorological experiments to extrapolate Q1 (heat), Q2 (moisture), momentum (Q3) tendencies due to cloud-scale processes. We propose that a "Q4" for CO and "Q5" for ozone be defined and used to assess the vertical exchange of air during conditionally unstable conditions. These measurements will provide a valuable additional set of observations that can be used to assess the performance of cumulus parameterization schemes.

Lagrangian experiment

A Lagrangian chemical experiment should be conducted as part of the CME. It would have as its objective investigations of pollutant transport and transformation through convective cloud systems using natural and artificial tracers. *This study will provide the basis for testing hypotheses and parametric schemes for convection-induced vertical exchange.* It should be possible to cover scales from penetrative nonprecipitating cumulus to well-organized mesoscale convective systems. Penetrative convection includes contributions of both the up and downdrafts to vertical exchange, as well as the products of cloud-induced aqueous-phase reactions. Outflow from organized convective clouds will provide information on venting of boundary layer pollutants into the free troposphere and lower stratosphere. Integration of nonprecipitating cloud and organized convection studies into the CME is envisioned. Descriptions of these two types of studies follow.

Nonprecipitating Cloud Studies

Inert tracers, SF_6 and perfluorocarbons can be released by aircraft, both above and within the mixed layer, during episodes of deep, penetrative cumulus convection. Mixtures of tracers from both mixed and cloud layers are subsequently sampled in mixed and cloud layers and also at the surface. Ratios of pollutant to tracer provide data on both mixing and aqueous transformation rates. Results are used to determine the overall transport due to an ensemble of nonprecipitating cumuli. Two sampling aircraft, as well as a tracer release aircraft and ground-based samplers are required. Sampling should also include natural tracers such as CO and O_3, as well as O_3 precursors NO_x and NMHC. Other CME studies

will provide ancillary information to facilitate the interpretation of the cloud studies and strengthen the evidence and conclusions to be drawn about vertical exchange processes.

Organized Convective Systems

To determine the degree of convective enhancement of O_3 production, an experiment must acquire sufficient data for accurate model verification. *The cloud-dynamical model requires observations over thousands of square kilometers with a ground-based network of soundings, profilers, at least two Doppler radars and aircraft flying in and near convective cells.*

Characterization of the chemical environment can be done with two aircraft and minimal surface instrumentation; however, a third aircraft with limited chemical instrumentation is strongly preferable. One aircraft must have altitude coverage and range to encompass a mesoscale convective system with anvil outflow at 10-12 km. As far as we know, only the DC-8 meets these requirements and can cover both cloud-disturbed and undisturbed air masses. A second plane is required to concentrate on measurements in anvil outflow, including flights downwind and in the initially perturbed region both early in the storm and for a number of hours after the convective event. This is the most critical element for verifying post-storm O_3 production. A third aircraft would be deployed in the lower and middle troposphere. One role of this aircraft would be to make measurements in the undisturbed boundary layer just ahead of the convective cell(s) for complete characterization of boundary-layer transport and chemistry in pre-convective conditions.

During a mesoscale convective experiment the focus of the meteorological community may be on one particular scale of convective phenomena, e.g. mesoscale convective complexes (MCCs), but nature may not cooperate and a different type of convection may predominate (such as squall lines and air mass thunderstorms). Measurements of the following species are considered critical to meet the objectives: CO, O_3, H_2O, NO, NO_2, NO_y, and NMHC. In addition, UV-DIAL O_3 and aerosol measurements would also be required for assessing redistribution and ouflow from a convective system.

Aerosols - heterogeneous chemistry

Aerosols and gases associated with heterogeneous cloud chemistry should be sampled according to the flight scenarios described for nonprecipitating cumulus and for organized convective systems. High-volume samples taken over constant-altitude flight legs should

be analyzed for NH_4^+, SO_4^{--} and other species. Shorter-time interval sampling should also be conducted and the samples analyzed for critical species. Cloud condensation nuclei (CCN) should be sampled both by aircraft and at the surface. The gases SO_2 and NH_3 should also be sampled from the aircraft and at the surface. These data will aid in understanding the behavior of sulfates and their relationship to CCN.

4.6 Joint sessions on validation of coupled models and techniques/resources for storm-scale numerical weather prediction

Bill Kuo and Kelvin Droegemeier

This joint session considered the recent modeling successes made with high resolution models which may be either nested within coarser mesh models or which may employ adaptive grid stategies. Suggestions for future multiscale model verification needs considered the special quality of these kinds of models. In addition, the requirements of coupled chemistry, land surface, hydrological, etc. models were considered by this group in making its recommendations.

4.6.1 Session on validation of coupled models

Bill Kuo

N94-24399

a. Current status

The use of a mesoscale model with a grid size of 20-km during STORM-FEST in 1992 has proven to be extremely valuable. The availability of forecast products at a much higher temporal and spatial resolution was very helpful for mesoscale forecasting, mission planning, and the guidance of research aircraft. Recent numerical simulation of ocean cyclones and mesoscale convective systems using nonhydrostatic cloud/mesoscale models with a grid size as small as 2-km have demonstrated the potential of these models for predicting mesoscale convective systems, squall lines, hurricane rainbands, mesoscale gravity waves, and mesoscale frontal structures embedded within an extratropical cyclone. Although mesoscale/cloud scale models have demonstrated strong potential for use in operational forecasting, very limited quantitative evaluation (and verification) of these models have been performed. As a result, the accuracy, the systematic biases, and the useful forecast limits have not been properly defined for these models. Also, no serious attempts were made to use these models for operational prediction of mesoscale convective systems.

b. *Most critical unknowns*

The problems of mesoscale model verifications can be summarized as follows:

- Conventional rawinsonde and surface observations have insufficient temporal and spatial coverage. These data are useful for synoptic scale model verification, but are of limited value for mesoscale model verification.

- Observations from upcoming mesoscale observing platforms have significant variations in measurement characteristics, data quality, and temporal and spatial resolution. Each of these observation platforms (such as the profilers, the ACARS observations, RASS, ground-based microwave radiometers, NEXRAD, and the GOES-Next satellites) by itself does not provide a complete decription of mesoscale weather systems.

- *The hydrological cycle appears to be the weakest component of operational and research models.* Unfortunately, moisture variables, which are crucial for validation of model precipitation parameterizations, are poorly observed.

c. *Specific recommendations*

- *Perform a comprehensive verification of mesoscale prediction, high quality "assimilated fields".* Therefore, it is essential to develop a "state-of-the-art" mesoscale data assimilation system to produce IIIb analysis for CME, with a horizontal resolution of ~10 km.

- The quality of the IIIb analysis must be evaluated carefully. This can be done either using some independent observations or by looking at the quality of very short-range forecasts.

- Meso-gamma scale data assimilation based on Doppler radar data should be encouraged. This will provide a detailed description of mesoscale convective systems at a horizontal resolution of 1 km. However, because of the large volume of data and the computing resources required, this type of data assimilation probably can only be done on selected cases at selected times.

- The meso-beta-scale and gamma-scale assimilated fields can then be used to initialize and verify cloud/mesoscale models

d. *Observational needs:*

- *For CME we need broad rawinsonde coverage at a variety of scales if we are to capture the genesis, development and dissipation stages of the MCS.* This is essential if we are going to advance cloud/mesoscale models for predicting the initiation and organization of mesoscale convective systems.

- *We need high resolution, high quality moisture measurements.* Such data are required to validate model hydrological processes. For example, can we accurately compute the water budgets on the scale of an MCS at a temporal resolution of about 1 h?

- We need high resolution (both in time and space) precipitation data for model verification.

- We need comprehensive dual Doppler radar coverage. Both airborne and ground-based radars are needed to provide detailed flow fields for the entire life cycle of a MCS.

N94-24400

4.6.2 Session on techniques and resources for storm-scale numerical weather prediction

Kelvin Droegemeier

The recommendations of this group are broken down into three areas: modeling and prediction, data requirements in support of modeling and prediction, and data management. The format in this section differs somewhat from that used in the previous workshop session descriptions, due to the more technical nature of the material.

I. Modeling and Prediction

a. Current Status

This group worked under the assumption that the CME would run a realtime forecast model in support of field operations and to evaluate the model's predictive capabilities as applied to MCS's and related phenomena. Additionally, the model would provide assimilated datasets for post-analysis. It is unlikely that massively parallel processing (MPP) systems will be utilized effectively enough by mid 1995 to play a role in this program, and thus the group recommended that the model be used on a more conventional (e.g., Cray-type) platform. However, if significant strides are made in MPP utilization during the next two years, an MPP option should be left open, particularly in light of the extremely large memories available on such machines. The NOAA Forecast Systems Laboratory recently completed an evaluation of current mesoscale models, and an even more detailed study of this type is being performed by the Air Force. The choice of a model or models for CME should be carefully orchestrated, with consideration given to model capabilities, efficiency, flexibility, and appropriateness for the CME mission.

b. Modeling and Technological Recommendations

The principal unknowns at this point, apart from the model itself, concern data, initialization methods, validation techniques, computing facilities, and data storage and display strategies. It is likely that *special computing facilities will be required* to support model execution and output archival, as well as collection of raw input data. The CME should determine which group or groups will bear this responsibility, and assess the need

for upgraded telecommunications capabilities. In order for the model to be effective in realtime, *appropriate data displays must be available.* The CME should explore the accomplishments of various groups in this area (e.g., FSL, University of Illinois). A model forecast duration of 18 hours is deemed optimal for the goals of the CME.

This group strongly endorses the use of adaptive grids in the realtime prediction support, though it is less vocal about the role of adaptive grids in creating the assimilated datasets for post-analysis. The most plausible strategy for adaptive refinement is to allow the program to make a "first guess" on optimal grid placement, with augmentations allowed by the person coordinating the model runs. Although fully automated grid placement is not yet available, ongoing developments may provide this capability by the mid-1990s (e.g., work is being conducted in adaptive grid refinement by W. Skamarock at NCAR, L. Wicker and Texas A&M, M. Xue and K. Droegemeier at CAPS, W.-K. Tao at NASA GSFC). CME should encourage these groups to make intercomparison studies of the various available models, and re-evaluate the state-of-the-art in adaptive refinement at various times prior to the field experiment. Thus, the CME should re-evaluate this recommendation prior to the actual field program.

Finally, this group wishes to underscore the limitations of a realtime forecast model. The CME should view the model as a tool for providing statistical or probabilistic guidance, out to 18 or so hours, and avoid relying on it too heavily for detailed guidance (see discussion of model validation below). The model used should probably be configured with a simplified set of parameterizations appropriate for the scales and phenomena being studies. A mix of guidance products (radar, model, surface and upper air data) will be optimal supplements to the model.

II. Data Requirements in Support of Modeling and Prediction

We recommend that *all* available data be used to define the model's initial state. Techniques to assimilate radial velocity and reflectivity data from WSR-88D systems should be pursued aggressively; however, it is unclear whether single-Doppler techniques (apart from VAD) will be mature enough for use by 1995. The choice of a model for this program should be made carefully, and only after a number of candidate codes have been examined in light of program requirements. The FSL has already performed such an exercise for its FAA-related programs, and this information might prove useful to CME. Most mesoscale models are initialized using analyses based upon NMC gridded fields, perhaps augmented by available profiler and surface net data. The FSL LAPS analysis, by virtue of its combined

data types, represents a possible "melting pot" for observations and thus could serve as the initial state for the mesoscale model to be used.

This group feels very strongly that moisture is ***the key*** *to successful prediction, modeling, and data assimilation in support of CME.* In order to provide high-quality and spatially-dense measurements, the group recommends the use of rawinsondes, perhaps a few of which are high quality "reference sondes". Additionally, a few Raman lidars, co-located with the sondes, would provide important ground truth measurements. It was felt that the CASH program could be a critical element of CME, provided that it was in place by the time of the field experiment. Other airlines should be encouraged to participate.

The importance of obtaining "raw" sonde data cannot be overemphasized. Through the various stages of data processing, a considerable amount of useful information is discarded from the sondes, including moisture at high levels. Further, the sounding data are sometimes truncated at levels around 200 mb, thus deleting important information. This group strongly urges the CME to make provision for the availability of raw sonde data, and to examine special release strategies to minimize data contamination by nearby storms. In addition, the CME should consider using only one brand of rawinsonde to ensure consistency.

Cloud water/ice were identified as important missing parameters in conventional observations, not only with respect to model initialization, but also for radiation budgets. Although various assimilation schemes might provide decent estimates of this variable, *cloud water and ice might be the Achilles heel of the modeling effort,* particularly with regard to the upper levels, where stratiform clouds play such a major role in radiative processes. Satellite rain retrieval algorithms can provide some information associated with the horizontal distribution of cloud water content, though the vertical distribution is less certain with such methods. Quantitative precipitation measurements were deemed critical for a number of reasons, particularly because soil moisture depends upon an accurate assessment of antecedent precipitation.

III. Data Management

Quite often in field programs, data management receives secondary consideration to science with regard to funding. A number of groups (e.g., FSL, UCAR Unidata) have developed sophisticated database archival systems, and thus the CME should avoid reinventing the wheel in this regard. It is not clear whether all data should be archived at a

single site, or whether multiple sites should be used. This group favors the single site strategy for the following reasons. First, a single large facility (e.g., NCAR) is more likely to be capable of handling large and multiple-type datasets. Second, such facilities have people dedicated to this task, whereas other options (e.g., universities) do not and would likely make data archival a secondary task. Finally, it would probably be easier to ensure consistency of formats and methods of access at a single facility.

This group strongly urges the CME to put sufficient resources into data management since the effective usefulness of the data collected depends, to a large degree, on the scientist's ability to access it. Given the quantity of data to be collected and generated by the model, data management is a much bigger issue than in previous field programs. We propose a heirarchical strategy that provides a user with quick-look data (e.g., a GIF-formatted image of a few radar display sequences that can be displayed on any X-windows compatible system) as well as complete menu-driven or command-line-interface driven query capability over the NSF internet. The CME should stress the use of common and machine- independent data formats (e.g., netCDF, GRIB, BUFR), and should work with developers (e.g., FSL, NCAR, Unidata) to make available basic workstation software to the user community. We suggest that suspect data be flagged, but not changed, during the quality control process, and reiterate that raw, rather than averaged, raob data be made available.

5. Summary

The Colloquium and Workshop on Multiscale Coupled Modeling was designed to bring together a diverse group of modelers, program managers, and other scientists to address modeling issues of importance to planning for the Cooperative Multiscale Experiment (CME). The primary purpose of the colloquium was to assess the current ability of numerical models to accurately simulate the development and evolution of mesoscale cloud and precipitation systems and their cycling of water substance, energy, and trace species. The primary purpose of the workshop was to make specific recommendations for the improvement of mesoscale models prior to the CME, their coupling with cloud, cumulus ensemble, hydrology, and air chemistry models, and the observational requirements to initialize and verify these models.

Meteorological programs that could benefit from a multiscale MCS study

Representatives from six meteorological programs each expressed a potential interest in collaborating together to achieve the unified purposes of the CME. In particular:

(1) The USWRP will make an effort to synergize with other programs to address the need for conducting a large multiscale experiment, versus the benefits to be gained from more focussed objective experiments. The proposed CME would benefit the USWRP by providing high resolution data for improving forecasting of precipitation and severe weather, the basic understanding of the limits of predictability and the nature of interactions between processes at the mesoscale and at smaller and larger scales, and understanding of the impacts of mesoscale weather events on hydrology. The USWRP recommends conducting OSSE-type experiments to first determine the need for a large number of rawinsondes in such an experiment.

(2) GCIP would benefit from a cooperative multiscale experiment by providing data for helping to provide closure on regional and mesoscale water and energy budgets, for initializing and verifying high resolution atmospheric models, land surface and convective parameterization schemes, and as input to hydrological models. GCIP is considering providing augmented observations in the form of additional soundings and surface energy budget stations for a 5-7 year period at some of the sites composing the profiler hexagonal array that surrounds the ARM/CART site.

(3) The focus of GCSS is to develop parameterization schemes for mesoscale cloud systems, including precipitating convectively-driven cloud systems like MCSs, in large-scale models. Observations from field programs that can adequately measure scale interactive aspects are required for comparison with cloud-resolving model simulations.

(4) The goal of GVaP is to improve the understanding of water vapor and its variability on all scales, a goal that would benefit greatly from a multiscale observing strategy. An implementation plan has been developed for a pilot phase, which includes operation of a Water Vapor Reference Station at the ARM/CART site for a continuous period of 3 months in late spring of 1995 and intensive intercomparison of water vapor sensors during part of this period.

(5) The ARM goals are to provide an experimental test bed for improving the treatment of radiative transfer in GCMs and to improve the parameterization and modeling of cloud formation, maintenance, dissipation, and related processes in GCMs. Some of the scientific issues that are critical to the ARM objectives require intensive measurements on a variety of temporal and physical scales. In addition to the regular measurements at the CART site, a series of intensive observational periods will be performed for short periods as well as participation in any cooperative field campaigns in the region.

(6) The AWP aims to improve the weather information provided to the aviation community. This program would also benefit from participation in a cooperative multiscale experiment by obtaining data for evaluation of aviation weather forecast products and by making it possible to evaluate the added benefit of enhanced data sets collected during the experiment on those forecast and analysis products.

The Cooperative Multiscale Experiment

The scientific objectives of the CME include increasing the understanding of: (1) how scale-interactive processes generate and maintain MCSs; (2) the relative roles of balanced and unbalanced circulations in MCS dynamics; (3) the predictability of MCSs; (4) the role of MCSs in large-scale atmospheric circulations and the relationship of MCS occurrence to

variations in large-scale flow; (5) what data bases are required to initialize and validate coupled cloud-resolving/mesoscale models, that may be further coupled with hydrological or chemical models; and (6) the optimal use of four-dimensional data assimilation to retrieve cloud and state parameters from remote sensing instrumentation. Bill Cotton's presentation on the CME emphasized the manifold reasons for why a multiscale experiment is required to understand MCSs and their interactions with other scales. The CME scientific steering committee has chosen the central United States as the location for study of mesoscale convective systems, because of a high frequency of MCS activity in the spring and summer months, the ability to transfer research results to the data-sparse tropical environment, and the availability of frequent, high density operational measurement systems in the central U. S. A cooperative experiment is needed, because even though the costs of implementing a multiscale experiment is reduced by the considerable observations already available there, the total additional observing systems needed to provide the necessary multiscale measurements is still quite expensive ($2-6M). A cooperative program is a wise investment of resources, so it is important that the above six programs join forces to implement such a multiscale experiment. Ideally, running the field experiment from mid-April to mid-August in 1995 would allow sampling both spring storms residing in a rather baroclinic environment and mid-summer storms which reside in a more barotropic, tropical-like environment.

Grand scientific challenges

Steve Koch highlighted differences between past convective field experiments and the present opportunity for a truly multiscale field experiment. Most convective field experiments in the past have attempted to resolve only the immediate scales of moist convection using network arrays that spanned two or three atmospheric scales at most, which has precluded a description of the entire life cycle of MCSs and their interaction with larger scale systems, the land surface, and trace species. Fortunately, observational, computer, and data assimilation advances now make it possible to simulate scale contraction processes from the synoptic scale down to the cloud scale, and interactions between complex meteorological, land surface, precipitation, chemical, and hydrologic processes with coupled, multiscale models. Thus, the time is finally right from a technical and observational perspective to conduct a multiscale, multi-disciplinary field experiment focused on the mesoscale convection problem. Since numerical models now have the capability to explicitly resolve mesoscale gravity waves, slantwise convection resulting from conditional symmetric instability, density current-like microstructures at the leading edge of cold fronts, mesoscale tropopause folds, detailed land surface characteristics, and many other

features which are inherently scale-interactive, it is extremely important to muster all the scientific forces which have an interest in these problems to develop a multiscale field experiment that contains meaningful meteorological, hydrological, and chemical observing and modeling elements.

Data assimilation and model initialization techniques

This session covered both current-generation approaches (intermittent and continuous data assimilation, and physical initialization) and next-generation (variational, adjoint) techniques. A major issue concerns precipitation data assimilation, in that there are serious problems in both assimilating techniques and the sources of hydrologic data. *The quality and interpretation of indirectly measured hydrologic cycle data need to be improved,* in conjunction with the development of techniques to retrieve hydrometeors, which are needed to infer latent heating profiles from satelilites and WSR-88D radars. In addition, techniques need to be developed to insert information about fluxes, transports, and other process rates (e.g., evapotranspiration, rainfall rates, and TOA radiative fluxes) into analyses in a consistent fashion.

At the convective scale, since the primary observing tool will be Doppler radars, the key issue is the determination of initial conditions for all model variables from measurements of radial velocity and reflectivity in combination with other larger-scale data. Many questions remain on the types of data needed, the spatial density and temporal frequency required and the amount of error the techniques will tolerate. Much work remains to incorporate adjoint methods into a data assimilation system for real time prediction of storm-scale flows. Specification of the initial conditions in regions where no radar data are available remains an unsolved problem. The use of multi-parameter radar to initialize microphysical processes in coupled models should be investigated further.

Critical areas for research with variational (or Kalman filter) approaches to data assimilation include the needs to treat discontinuous processes (e.g., cumulus convection), reduce the huge computational requirements, and obtain meso- and cloud-scale error covariance statistics (*which can only be obtained from multiscale measurements*). Nudging approaches that employ variational techniques to define relaxation coefficients need to be further developed and tested to determine their usefulness in mesoscale models.

Measurement and modeling of moist processes

Excellent results have been obtained with coupled meso/cloudscale models when simulating squall line or other convective systems that are strongly forced by fronts or other lifting mechanisms. Less highly forced systems are difficult to model, particularly in nearly barotropic environments. In such cases, accurate predictions of MCSs may require: details about soil moisture, vegetation, outflow boundaries, and gravity waves triggered by earlier convection; either improved cumulus parameterization schemes or explicit simulation of deep convection over large domains; and increased upper air sampling to capture weak short-waves and jet streaks.

Knowledge of the three-dimensional mesoscale structure of the moisture field at frequent time intervals was echoed by this group, in addition to most of the other groups at the workshop, as the most crucial required measurement for CME. Concerning the measurement of water vapor, cloudy conditions compromise the measurements of most remote sensing systems, although use can be made of satellite cloud classification schemes to provide three-dimensional relative humidity fields in cloudy conditions. MCS measurement strategies must extend well beyond the "visible" cloud boundaries, and must not be limited to the dynamically active stages of MCSs, but also include observations of "fossil" MCS residue. In fact, all the important sources and sinks of moisture associated with MCS genesis and evolution (e.g., large-scale advection, evapotranspiration, precipitation) must be identified in three dimensions and with sufficient temporal resolution to be useful for developing, improving, and verifying sub-grid scale parameterization schemes. Additional needs exist to: couple aerosol and cloud microphysics models, obtain measurements of aerosols and hydrometeor spectra for radiation calculations, and provide soundings over the eastern Pacific to identify sub-tropical jets and jet streaks entering the southwest and impacting the MCS genesis region. An *urgent need* exists to integrate satellite, surface and radiosonde data to provide mesoscale analysis of moisture required for further development and validation of coupled multiscale models. *Hydrological cycle improvements are critically needed* to not only produce accurate precipitation in all kinds of situations, but also to transport moisture vertically and to improve upon model treatments of clouds as they relate to the radiative budgets by using explicit prediction of condensate fields and knowledge in the initial state of the models of the cloud bases, tops, and optical properties.

Parameterization of sub-grid scale convection

The relative importance of convective heat and moisture processes is scale-dependent: whereas in climate models it is crucial that the parameterization predict the proper

evolution of the moisture field, at the mesoscale it becomes extremely important to predict the location and rate of convective latent heat release, as the evolution of mesoscale systems is highly dependent upon the diabatic heating. Most current cumulus parameterizations do not appear to be valid when applied on grid meshes smaller than about 20 km, but when the grid mesh becomes greater than about 2 km, explicit moisture schemes tend to produce unrealistically large vertical drafts. Research is needed to determine the best methods of simulating convection for grid meshes between 2 - 20 km. There are *no existing data sets* with sufficient temporal and spatial resolution to verify closure hypotheses contained in cumulus parameterization schemes. The data must be able to separate the convective response to grid-scale changes from the grid-scale response to convection. This will require very high temporal resolution data over multiple scales to analyze complex interactions between clouds and the mass field, as well as in-situ measurements of thermodynamic properties and hydrometeors. Rather than direct tests between existing parameterizations, what is needed is to isolate the major assumptions used in each scheme and test these assumptions within carefully controlled experiments in which all other components of the scheme are similar.

Effects of the moisture field on convection and vice-versa need to be better understood. Further research is needed to develop cumulus parameterization approaches that predict convection in terms of the physical processes that directly cause clouds to form. In addition, development of MCS momentum-exchange parameterization techniques is badly needed, particularly for climate models and other coarse-grid models. However, the *most critical process that needs to be determined to improve cumulus parameterizations is the rapid interaction between the clouds and the mass field on meso-beta through synoptic scales.* The best way to infer these interactions is by observing the divergent component of the winds. It should be possible to use wind profilers to interpolate in time between rawinsonde sampling times. In addition, high temporal and spatial resolution measurements of the three- dimensional atmospheric winds on the scale of 2-20 km need to be obtained using doppler radar. *Convection is much more of a multi-scale phenomenon than is commonly realized; experiments that have focused only on the structure of individual clouds or MCSs have not been able to resolve the nature of the processes that cause convection or to document the complete effects of convection upon larger scales.*

Coupled land surface/hydrologic/atmospheric models

Evapotranspiration modeling presents the most serious challenge in these coupled models, because of its complexity, yet its importance to the development of convection.

Soil-water content is the single most important land-surface variable in atmospheric prediction models. There is *a critical need for time-series measurements of soil moisture profiles* to complement other mesoscale data, particularly in the dryline-prone regions of the High Plains contained within the CME enhanced observational area. Explicit modeling of the fully interactive relationship between the heterogeneous surface, boundary layer and clouds can lead to more accurate predictions of cloud onset and amount over land surfaces. The CME presents opportunities to expand upon our present inadequate knowledge of mesoscale circulations forced by inhomogeneous land surface characteristics, and to develop approaches for parameterizing their effects in mesoscale and larger-scale models. The linkage between boundary-layer thermals and the characteristics of the underlying surface also should be investigated in CME. The influence of spatially coherent fluxes that result from landscape heterogeneity are not included in current models. Fortunately, valuable representations of several aspects of the landscape pattern currently exist, including digital elevation data and measures of the leaf area index (i.e., NDVI from AVHRR data). *A major deficiency*, however, is the lack of an ability to sample spatially representative shallow and (especially) deep soil moisture. Numerous mesoscale modeling and observational studies have demonstrated the sensitivity of planetary boundary layer structure and deep cumulonimbus convection to the magnitude of the surface moisture flux.

Latent heat, sensible heat and net radiative fluxes are needed at enough sites to characterize means and variability in order to scale up from the hydrology catchment scale to the MCS scale. It was recommended that high-resolution OSSEs should be conducted to examine sensitivity of the atmosphere to the quality, distribution, and sampling of various land surface and vegetation parameters prior to CME. Specific measurements that may be needed include vegetation cover, soil characteristics, and terrain data on 1 km scales, recording and archiving of WSR-88D data, automated soil moisture profiles by neutron probe, dual ground based Doppler lidar to characterize boundaries, and new types of measurement platforms for economical boundary layer measurements such as instrumented radio-controlled aircraft. The CME planning committee should also incorporate satellite remote sensing technologies, especially FIFE results, into the project design and operation.

There is a need to permit two-way interactions between the atmosphere, and biophysical and hydrologic processes. This feedback is essential in order to properly represent the control on transpiration of water into the boundary layer environment. These interactions point to the necessity for interdisciplinary activities in the CME. Involvement by the hydrology, ecology, and chemistry communities would be mutually

beneficial. For example, since stomatal conductance of water is directly related to carbon dioxide fluxes, these models must also influence dry deposition of other chemical species, particularly hydroscopic aerosols and gases. Likewise, meteorological models require knowledge of soil hydraulic properties for input to surface layer parameterizations. Correspondingly, an accurate characterization of precipitation, evapotranspiration, and landscape structure is necessary for input to hydrology models. A similar relationship exists with the ecological modeling community. Atmospheric models are strongly affected by vegetation processes, while the ecological community needs atmospheric information to properly simulate soil and vegetation biophysics (e.g., the soil carbon budget).

Incorporation of the planetary boundary layer in atmospheric models

The planetary boundary layer (PBL) plays a crucial role in coupled mesoscale systems, because of its importance in transporting momentum, heat, and moisture from the surface into the systems. Despite major progress over the last two decades in modeling the PBL, *very little is known about the influence of mesoscale variability on PBL and turbulence statistics,* since the parameterization of boundary layer processes for use in larger scale models has been based almost exclusively on observations collected for horizontally homogeneous surface conditions under simple, slowly time-varying synoptic weather conditions.

Another issue concerns how cumulus-induced subgrid-scale effects should be included. Mesoscale cloud systems strongly modify the underlying PBL structures due to the effects of detraining cumulus downdrafts, cumulus-induced subsidence, cloud cover modulation of radiation inputs into the PBL, and rain evaporation. Since these modifications often change the subsequent mesoscale system development, it is important to incorporate these modifications into PBL parameterizations. For example, it is not clear how to incorporate the formation and dissipation of PBL stratiform clouds in models, yet frontal systems are typically associated with such clouds. Often too thin to be resolved in the vertical grid, these stratiform clouds need to be included in the PBL parameterization. Stratus-type clouds and their effects on mesoscale systems are deserving of much study, since not only do these clouds play an important role in the climate-radiation budget, but they may also be important for the development of mesoscale frontal system circulations. A stratus-topped PBL is much more complicated and less understood than clear PBLs, because its structure is strongly affected by many additional physical processes.

In order to better understand the underlying PBL effects on MCSs, we need to learn first how the PBL structure evolves along with the overlying convection and how it varies spatially within the system. For this purpose, *we need to design field experiments that can simultaneously measure the PBL and the overlying convection.* This may require using aircraft, acoustic sounders, wind profilers, lidars, and radars simultaneously. *The use of chemical species as tracers* in observing the transport properties of PBL turbulence and clouds was highly recommended. Before the CME takes place, we need to gather information on what prior field experiments have and have not learned.

Funds should be provided not only for carrying out field programs, but also for their design and for the analysis of their data. *Formation of a working group to evaluate and develop PBL models in the mesoscale context would be highly beneficial to CME.* Although large-eddy simulations (LES) should play a major part in such an evaluation, the LES database is limited to horizontally homogeneous PBL types. We must depend on observations for more complicated PBL cases. We may also want to apply this evaluation process to coupled land process-PBL models, coupled cumulus parameterization-PBL models, and coupled air chemistry-PBL models.

The role of radiation in mesoscale flows: physics, parameterizations, codes

It is vitally important to expand our basic knowledge of how MCSs influence climate through their extensive cloud shields and increase of humidity in the upper troposphere. In order to accomplish this task, it will be necessary to improve radiation parameterizations used in mesoscale and GCM models. One of the most critical problems facing modelers presently is that no consistent radiation-microphysical coupling exists in current mesoscale radiative transfer schemes. *It will be extremely helpful to develop and validate a community radiative transfer code suitable for use with mesoscale models, and to establish an intercomparison project to isolate and understand radiative processes in mesoscale models.*

Equally important is the need to improve our understanding of the influence of radiation and cloud microphysical properties on MCS dynamics due to diabatic heating, production of condensate, and vertical and horizontal heat fluxes. Observational requirements concern the needs to determine MCS related cloud optical properties, such as optical thickness, their morphology, and microphysical composition. It should be a *major* scientific objective of CME to provide observations to establish the radiative budgets of different kinds of MCSs *throughout* their entire life cycle. It is also essential to consider

how to convincingly present results from mesoscale models and field studies in their more global climate context, and how experiences in other radiation and climate related projects (ARM, FIRE, etc.) could contribute to the design of the CME field project.

Chemistry on the mesoscale: modeling and measurement issues

This session reviewed the current knowledge and research needs for chemistry on the meso and cloud scales. First, tropospheric ozone is a multiscale problem (urban, regional, global). Treatments of surface and boundary layer processes (including natural HC emissions from vegetation) and cloud venting are required for understanding the production and distribution of ozone in the troposphere. Uncertainties that exist in many modules of regional and cloud-scale chemical models could be reduced by incorporating chemical measurements and modeling into the CME. Conversely, the use of chemical tracers in a CME can help define air motions on both cloud and mesoscale. A major model limitation is that deposition of trace gases to the surface and emission of other species from the soil and from vegetation need to be better specified in the models. In addition, the simulated diurnal variation of the boundary layer depth needs to better follow observations. Cloud microphysical schemes and treatment of radiational characteristics within and surrounding a cloud remain the largest uncertainties of cloud-scale models. When photochemical models are run in conjunction with cloud models, there are large uncertainties in the photolysis rates within and above the cloud. *These models are limited by a lack of observational data to verify convective transport of ozone precursor gases and subsequent ozone production.* In particular, confirmation of the predicted magnitudes of cloud outflow and downstream photochemical ozone production is needed in a concerted chemical-mesoscale field program. Also needed is *vastly* improved information on the role of cloud microphysical processes in chemical scavenging and the role of lightning in NO formation.

Specific observational requirements consist, first of all, of the need to supplement surface hydrology and meteorology field studies in CME with chemical flux measurements to enhance the data base for deposition and emissions for use in regional modeling. Fluxes of CO_2, O_3, NO_x, and NO_y should be measured in conjunction with fluxes of sensible heat, latent heat, soil heat, as well as albedo and vegetation characteristics. Profiles of these species should be measured simultaneously with those of temperature, humidity, and winds. Scale issues should be addressed over heterogeneous land use and terrain. Using measurements of chemical species concentrations as passive tracers in the vicinity of convective storms, it is possible to directly assess the dynamic exchange of air within an

atmospheric column. This group proposed that carbon monoxide and ozone budgets be defined and used to assess the vertical exchange of air during conditionally unstable conditions. *These chemical measurements will provide a valuable additional set of observations that can be used to assess the performance of cumulus parameterization schemes.* Furthermore, inert tracers like SF_6 and perfluorocarbons can be released by aircraft, both above and within the mixed layer, during episodes of deep, penetrative cumulus convection to determine the overall transport due to an ensemble of nonprecipitating cumuli. Concerning the need to determine the degree of deep convective enhancement of ozone production, the CME must acquire sufficient data over thousands of square kilometers with a ground-based network of soundings, profilers, at least two Doppler radars and aircraft flying in and near convective cells. Characterization of the chemical environment can be done with two aircraft and minimal surface instrumentation; however, a third aircraft with limited chemical instrumentation is strongly preferable.

Validation of mesoscale models

Recent numerical simulation of ocean cyclones and mesoscale convective systems using nonhydrostatic coupled cloud/mesoscale models with a grid size as small as 2-km have demonstrated the potential of these models for predicting MCSs, squall lines, hurricane rainbands, mesoscale gravity waves, and mesoscale frontal structures embedded within an extratropical cyclone. Although these models have demonstrated strong potential for use in operational forecasting, very limited quantitative evaluation (and verification) of the models has been performed. As a result, the accuracy, the systematic biases, and the useful forecast limits have not been properly defined for these models. It has been shown that systematic errors in predicted synoptic-scale fields adversely affect a model's ability to predict MCSs. No serious attempts have yet been made to use such models for operational prediction of mesoscale convective systems.

The key element in verifying mesoscale forecasts is the availability of mesoscale observations. In order to perform a comprehensive verification of mesoscale prediction, high quality "assimilated fields" are needed. Therefore, it is *essential* to develop a "state-of-the-art" mesoscale data assimilation system to produce IIIb analysis for CME, with a horizontal resolution of ~10 km. Broad rawinsonde coverage at a variety of scales is needed if we are to capture the genesis, development and dissipation stages of the MCS. This is *essential* if we are going to advance cloud/mesoscale models for predicting the initiation and organization of mesoscale convective systems. High resolution, high quality moisture measurements (including precipitation) are required to validate model hydrological

processes. Finally, *comprehensive dual Doppler radar coverage is required* to validate couple meso/cloudscale model simulations of MCS circulations. The scientific steering committee for CME should also consider collaborating with the COMPARE project by providing a set of scientific hypotheses to be verified by coordinated numerical experimentation using data and analyses drawn from a CME event.

Techniques and resources for storm-scale numerical weather prediction

This group recommended that the CME define a model (s) to be used for both real-time forecast assistance in the field operations, as well as for assimilating the observations and to evaluate the model's predictive capabilities. The choice should be carefully made, with consideration given to model capabilities, efficiency, flexibility, and appropriateness for the CME mission. The model should probably be configured with a simplified set of parameterizations appropriate for the scales and phenomena being studied. The CME also needs to determine which groups will bear the responsibility of providing special computing facilities to support model execution and output archival.

Other principal unknowns at this point concern data, initialization methods, validation techniques, computing facilities, and data storage and display strategies. It will be necessary to assess the need for upgraded telecommunications capabilities. In order for the model to be effective in realtime, appropriate data displays must be available. The CME should explore the accomplishments of various groups in this area. *The use of adaptive grids was strongly endorsed in the realtime prediction support,* though the role of adaptive grids in creating the assimilated datasets for post-analysis is not so strongly advocated. CME should encourage groups to re-evaluate the state-of-the-art in adaptive refinement at various times prior to the field experiment.

This group felt very strongly that moisture is the key to successful prediction, modeling, and data assimilation in support of CME. In order to provide high-quality and spatially-dense measurements, the group recommends the use of rawinsondes, perhaps a few of which are high quality "reference sondes". Additionally, a few Raman lidars, co-located with the sondes, would provide important ground truth measurements. It was felt that the CASH program could be a critical element of CME, provided that it was in place by the time of the field experiment. The CME should make provision for the availability of *raw* sonde data, and examine special release strategies to minimize data contamination by nearby storms. In addition, only one brand of rawinsonde should be used to ensure consistency. *Cloud water/ice were identified as important missing parameters* in

conventional observations, not only with respect to model initialization, but also for radiation budgets. Although various assimilation schemes might provide decent estimates of this variable, it might be the Achilles heel of the modeling effort, particularly with regard to the upper levels, where stratiform clouds play such a major role in radiative processes.

Finally, from both political and scientific viewpoints, it would be wise to emphasize linkages between CME and climate. For example, medium-range prediction experiments could be conducted to assess the impact on their accuracy of CME data. Further, the CME data could be used to validate parameterizations used in global models, and to make assessments regarding the impact of orphan MCS cloud residue on medium- and long-term predictions and climate change. Finally, most cloud-impact climate studies have been focused on the tropics, where the moisture content at mid- and upper-levels is a key element in cloud- radiative forcing. The CME could uniquely provide information on moisture transports from the tropics to mid-latitudes, with emphasis on global responses.

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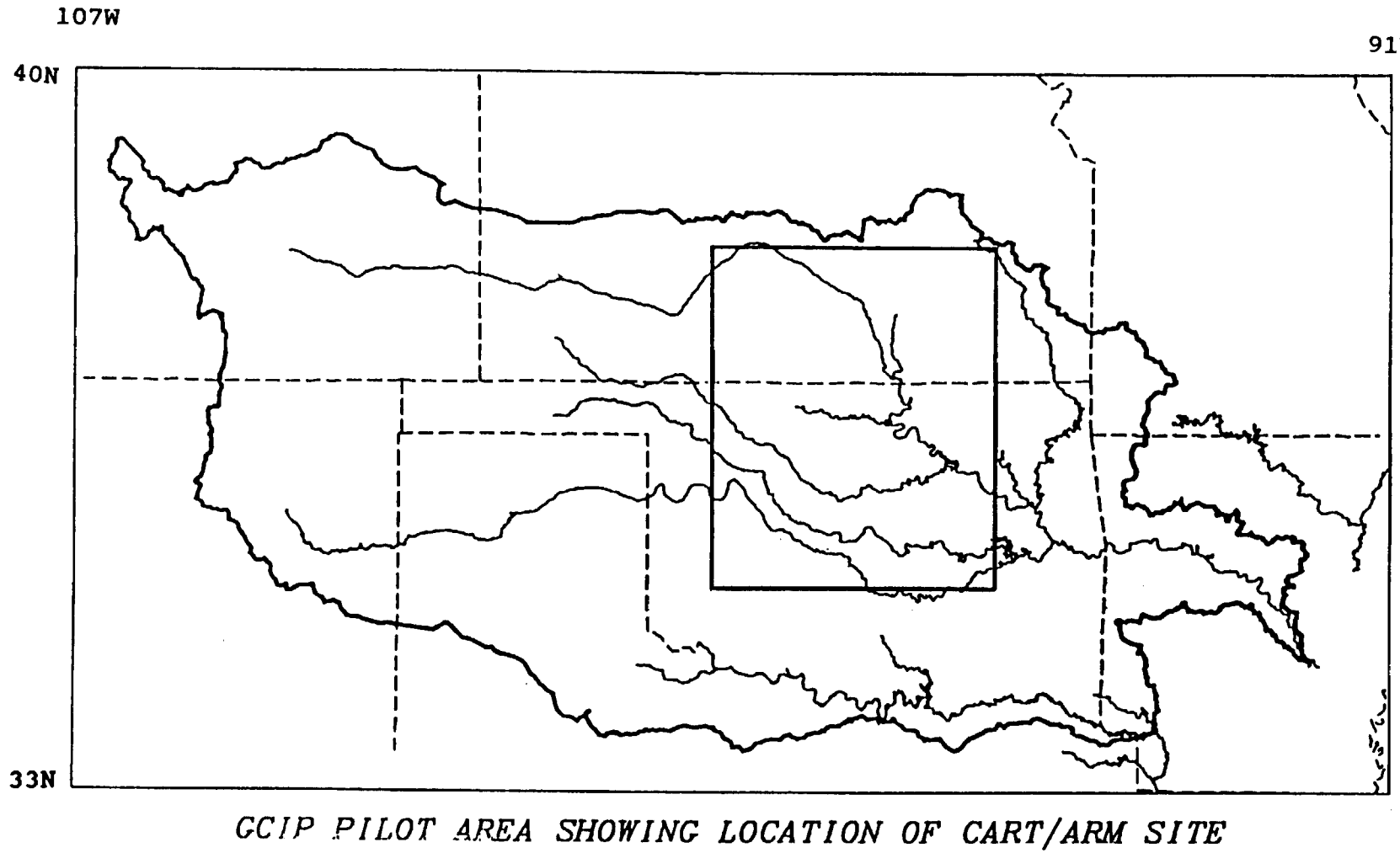


Fig. 1 The GCIP Integrated Systems Test (GIST) area as proposed in the current draft of the GCIP Implementation Plan. Note location of ARM/CART site (rectangle) in northern Oklahoma and southern Kansas. The region of responsibility of the Tulsa River Forecast Center (containing the Red River and Arkansas River watersheds) is shown, along with the major tributaries.

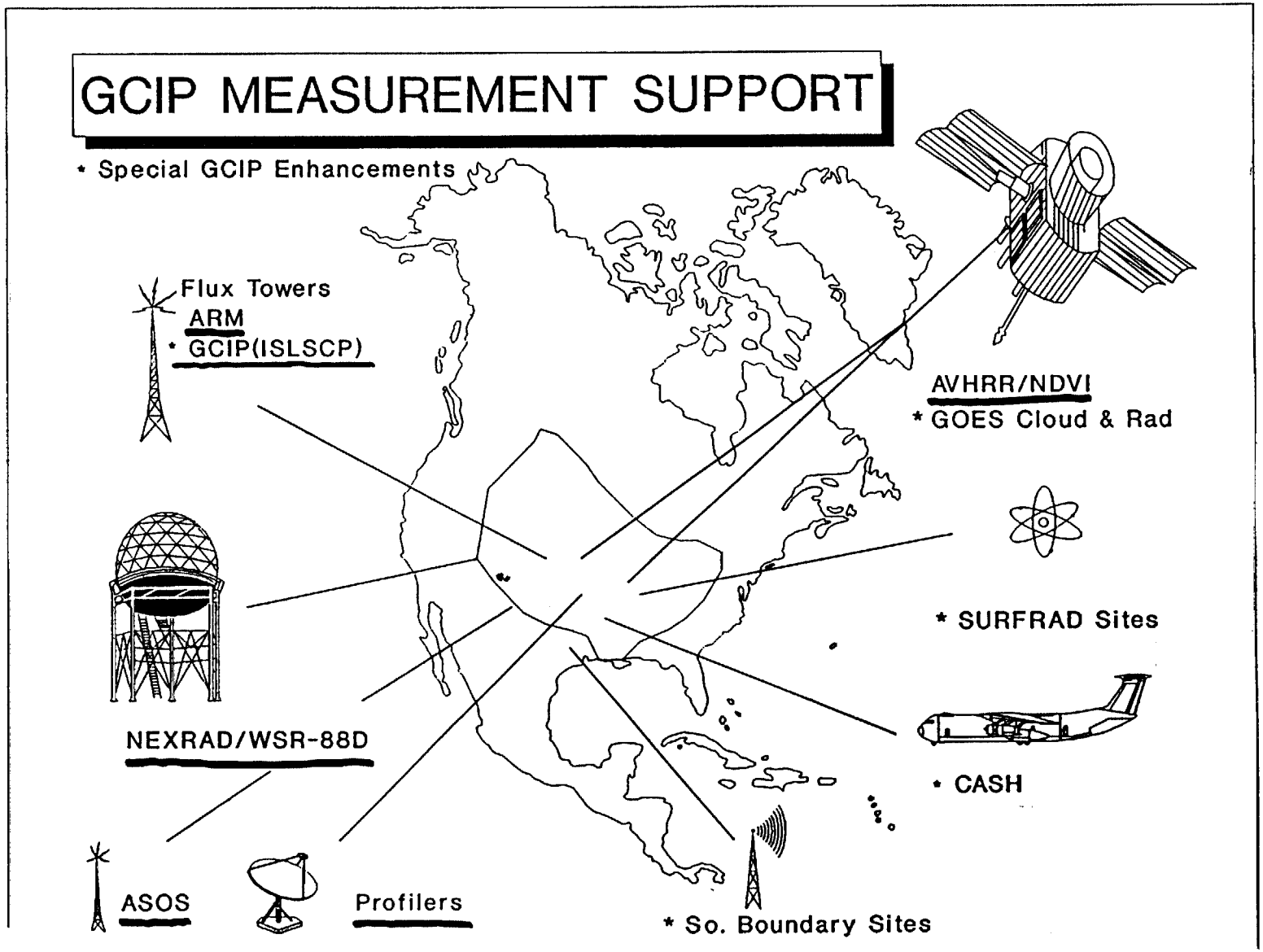


Fig. 2 The GCIP supporting measurement systems within the GCIP observing region (the Mississippi River Basin). Currently proposed augmentations to the nation's present or planned observing systems are noted with an asterisk (*), and include a network of 10-15 radiative flux towers (some of which may be located in the inner "hexagon" of wind profilers), boundary layer wind profilers located along the southern boundary of the U.S. and perhaps in the wind profiler hexagonal network, additional soundings at the "hexagon" sites, surface energy balance (SURFRAD) sites, and new cloud products derived from satellites and ASOS, and calibrated with the SURFRAD data.

CONTRIBUTION OF PRINCIPAL PROGRAMS TO GCSS

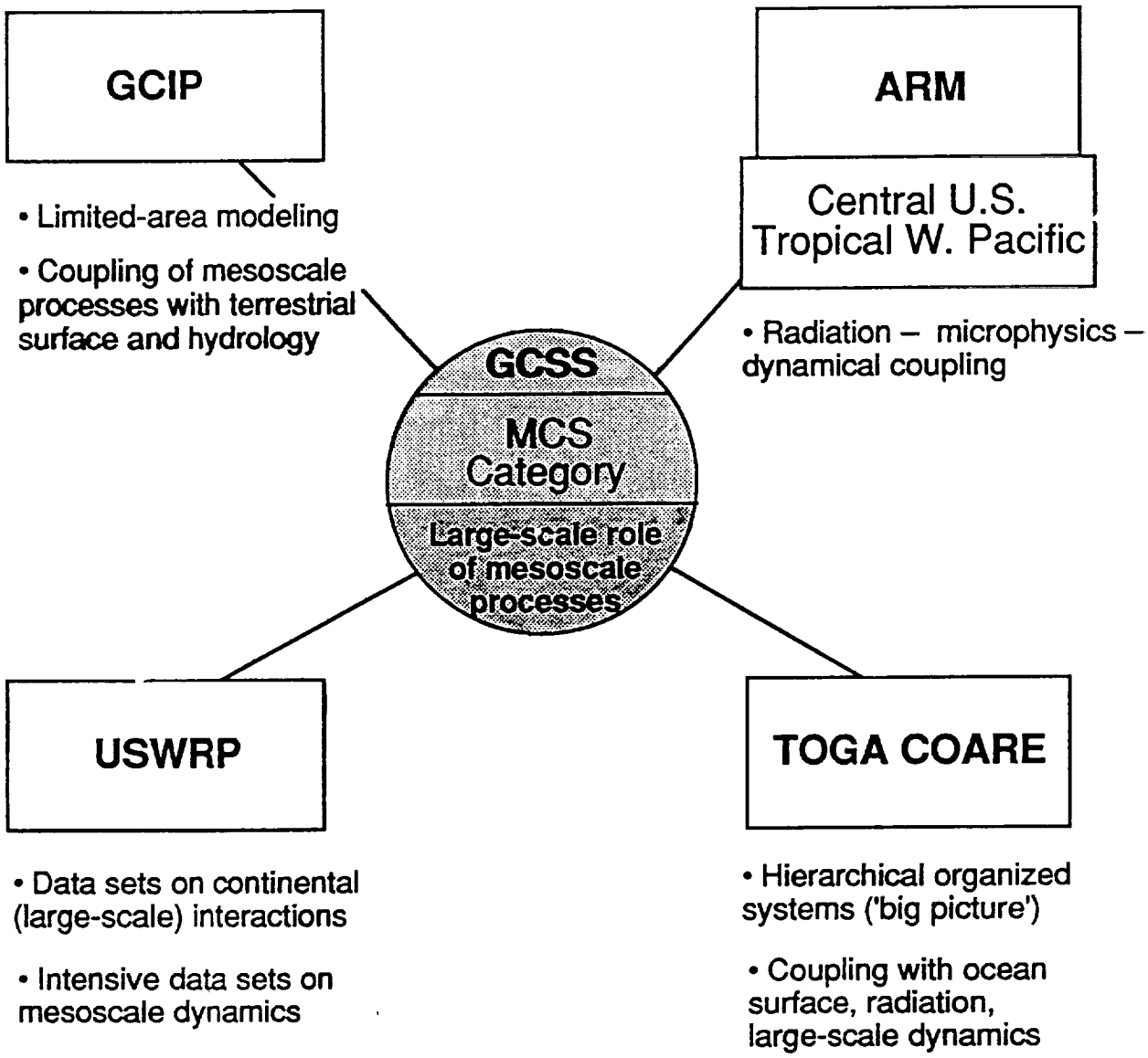


Fig. 3 The relationship of GCSS to other principal programs.

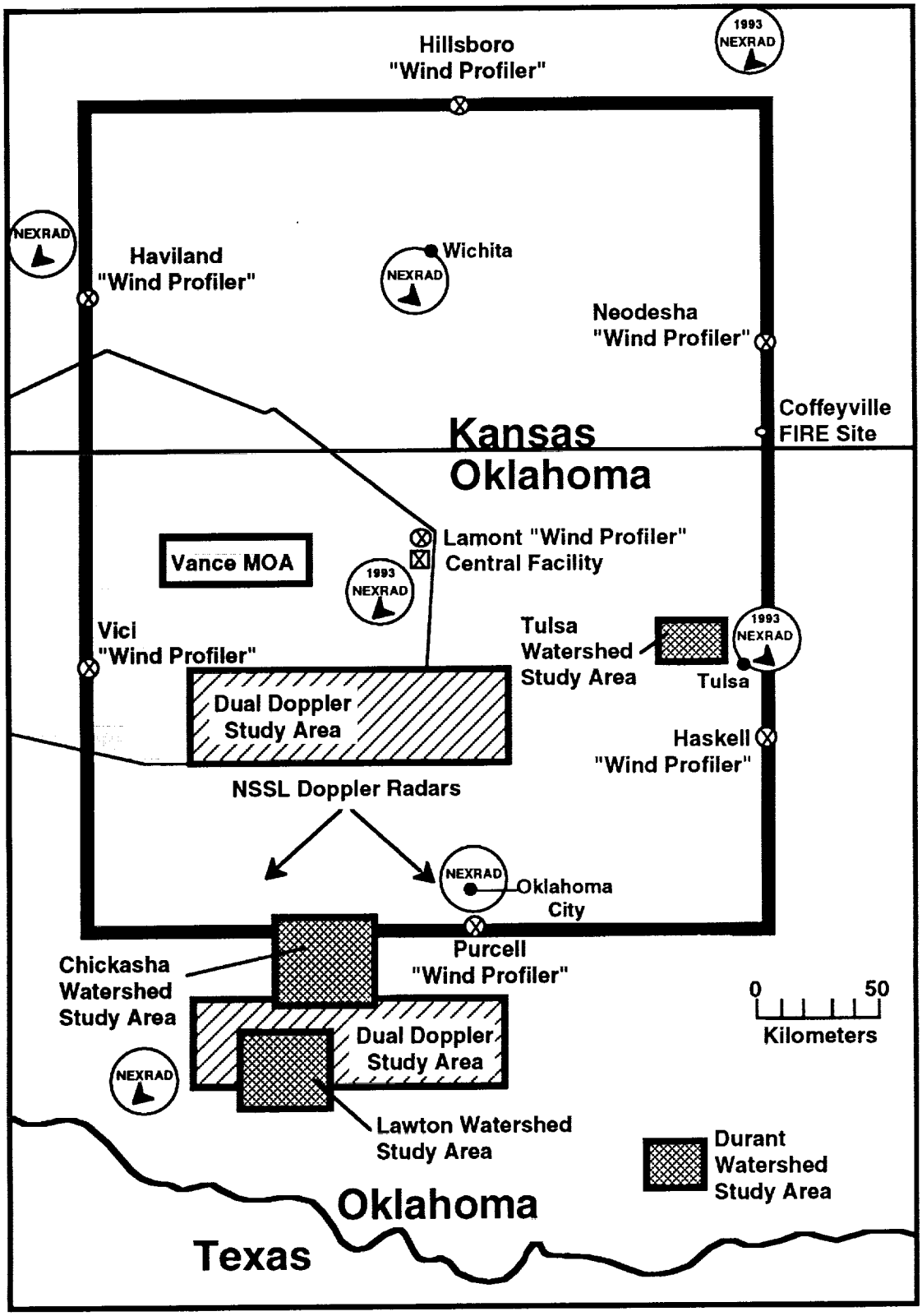


Fig. 4 The ARM/CART site and its relationship to other nearby observing systems, including the NEXRAD facilities, the inner hexagon of wind profilers, various watersheds, and the National Severe Storms Laboratory dual Doppler radars.

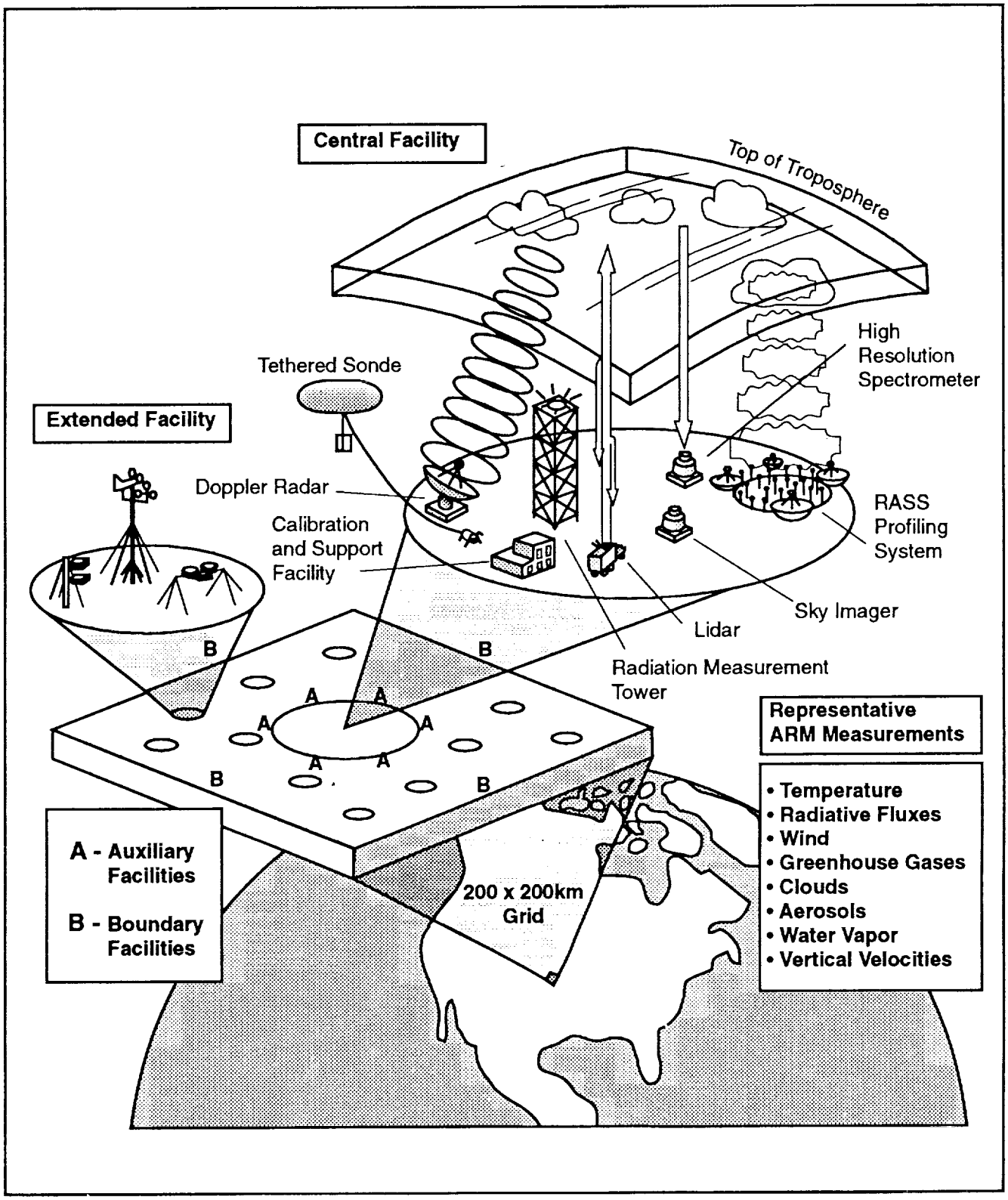


Fig. 5 The sensor components of the CART central facility and extended (auxiliary and boundary) facilities.

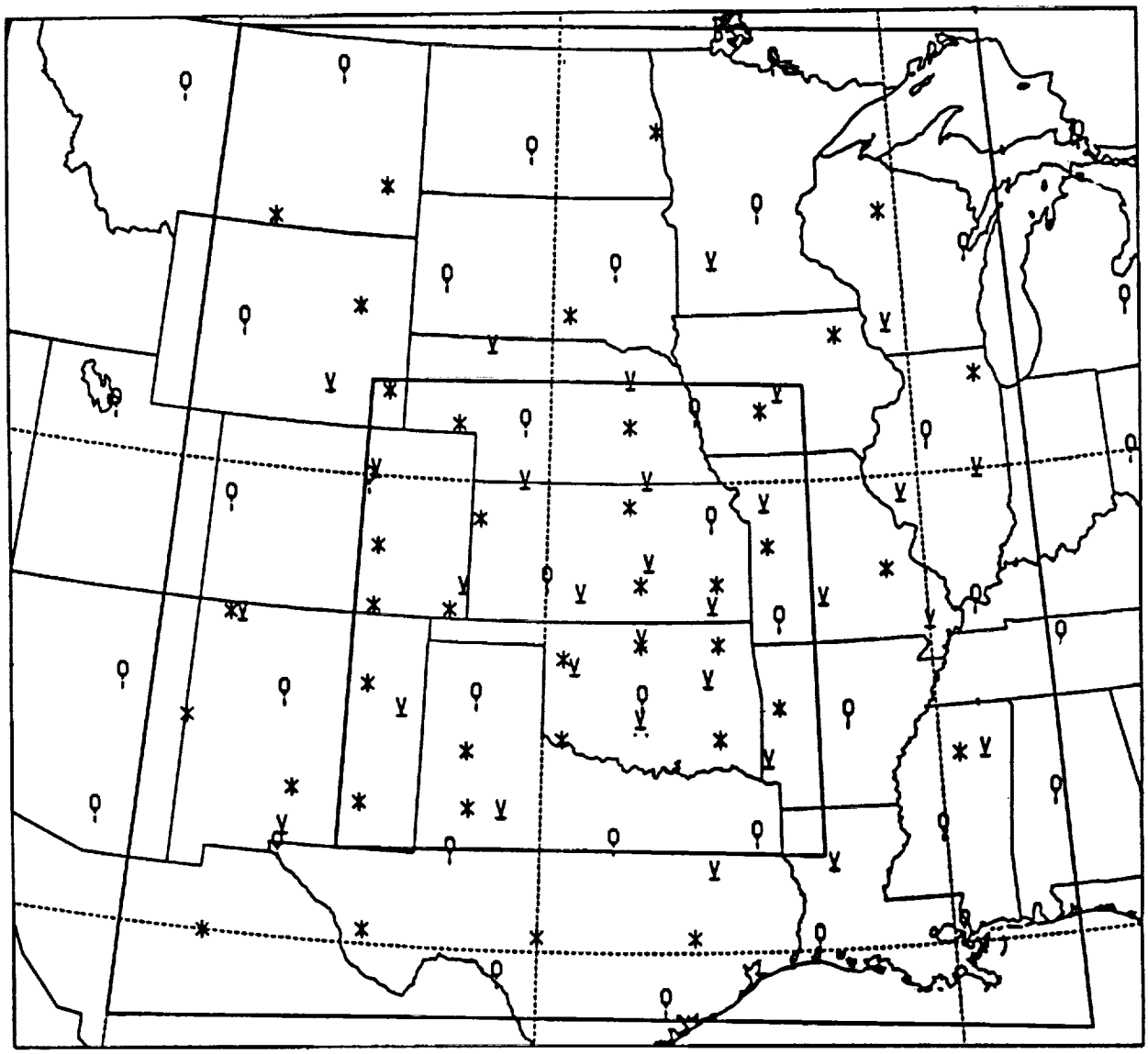


Fig. 6 The meso-alpha and meso-beta scale National Weather Service and supplemental sounding sites proposed for the Cooperative Multiscale Experiment.

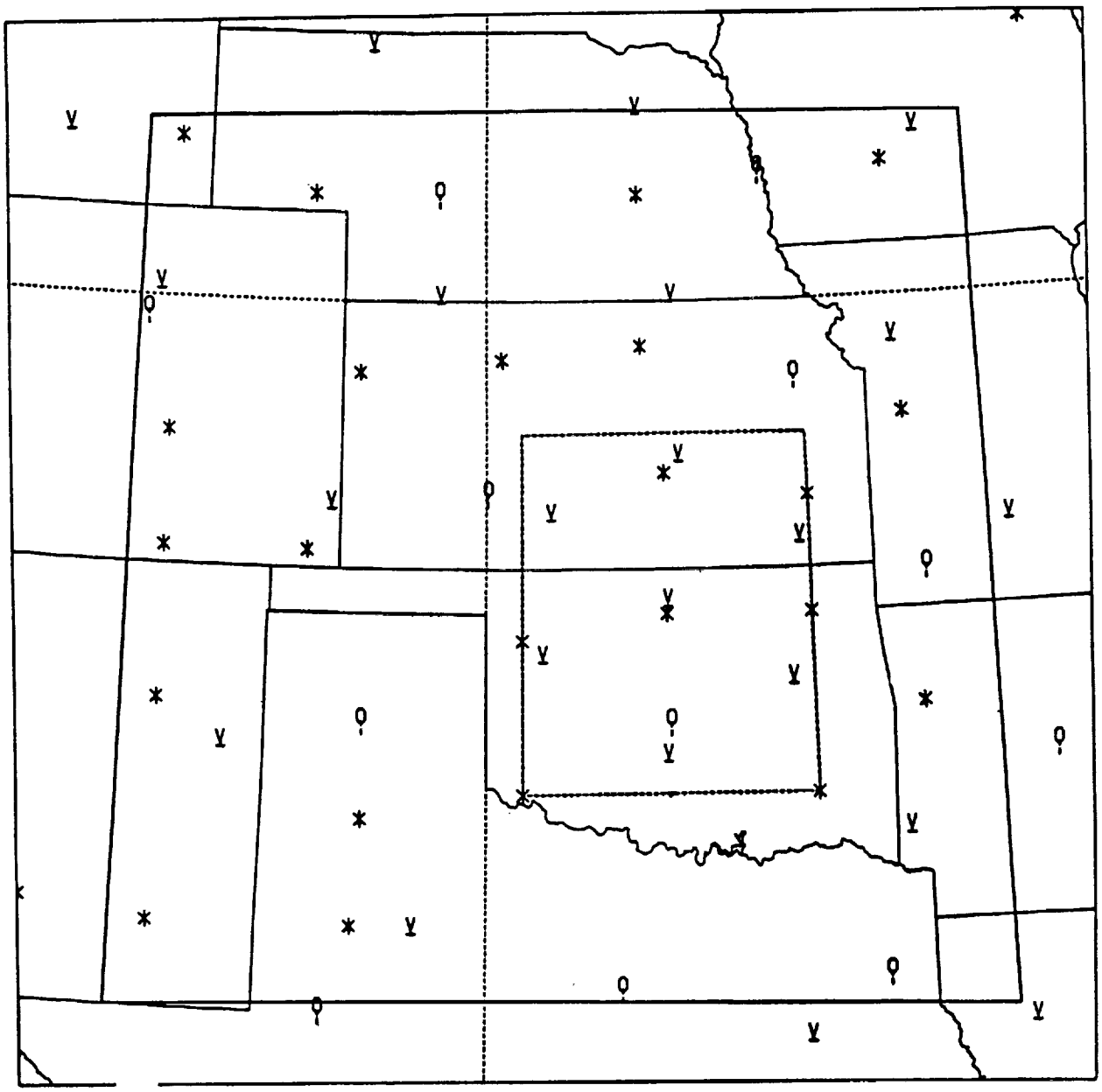


Fig. 7 The meso-beta scale National Weather Service (0) and supplemental (*) sounding sites proposed for the Cooperative Multiscale Experiment. Also shown are the Demonstration Wind Profiler locations and the ARM/CART site.

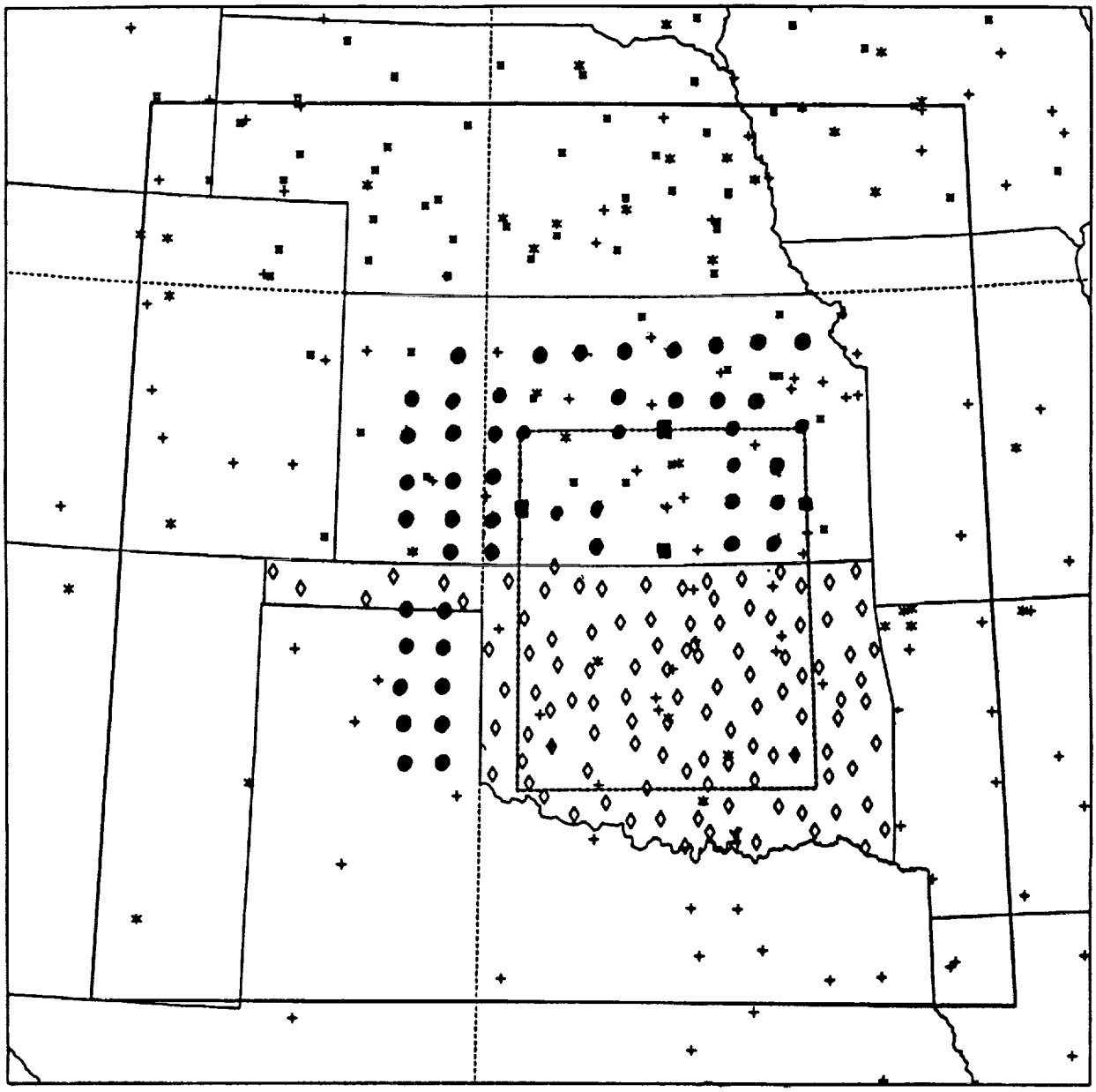


Fig. 8 The surface networks proposed for the Cooperative Multiscale Experiment, consisting of proposed PAM II sites (dots), and expected ASOS (+), AWOS (*), High Plains Cooperative Network (small boxes), and Oklahoma mesonetwork (diamond) sites.

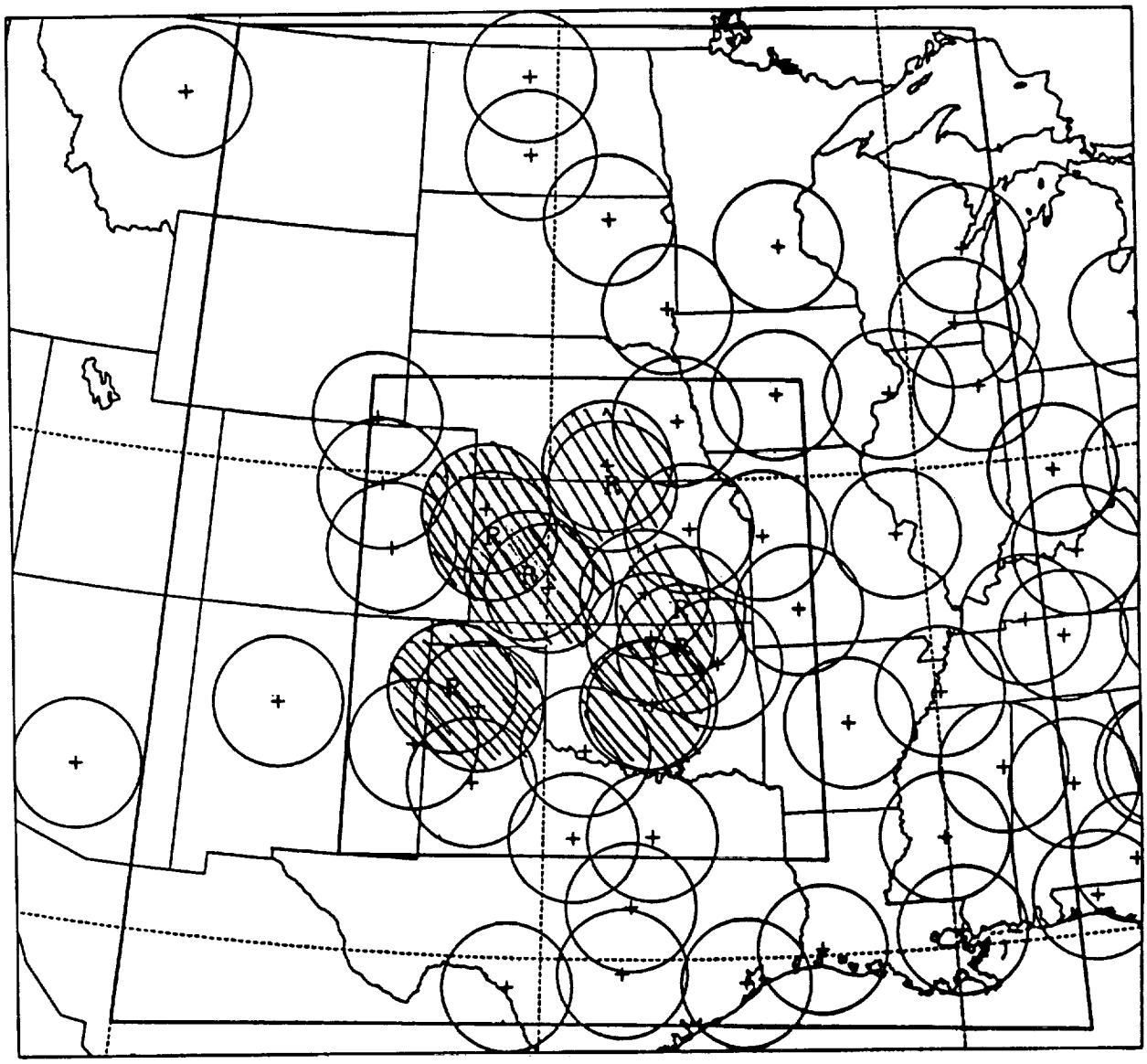


Fig. 9 The NEXRAD radar sites (open circles) and proposed research Doppler radar sites (hatched circles) proposed for the Cooperative Multiscale Experiment. Range circles are 100 km radius.

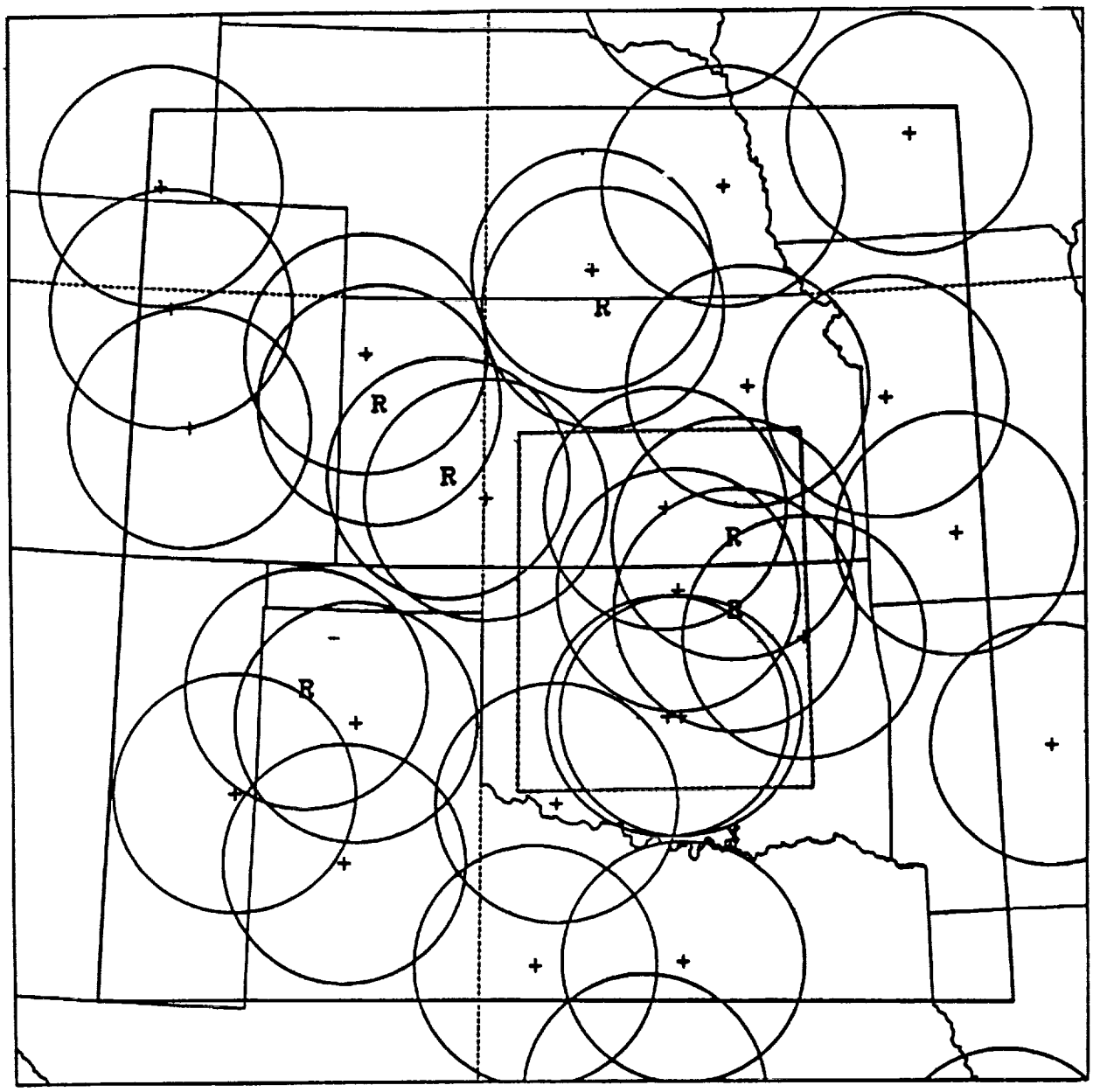
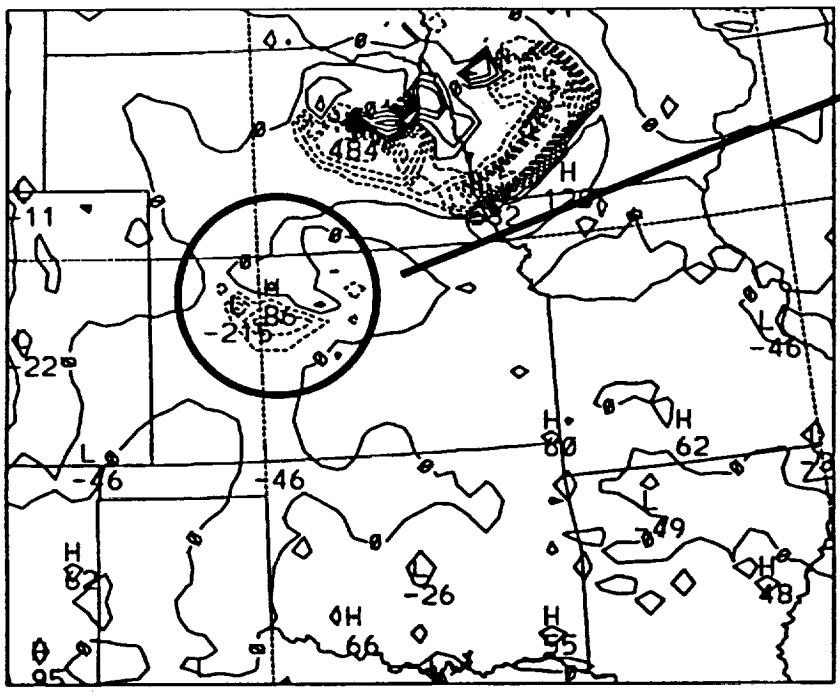


Fig. 10 The proposed beta-network radar sites proposed for the Cooperative Multiscale Experiment, consisting of NEXRAD (+) and research Doppler radars (R).

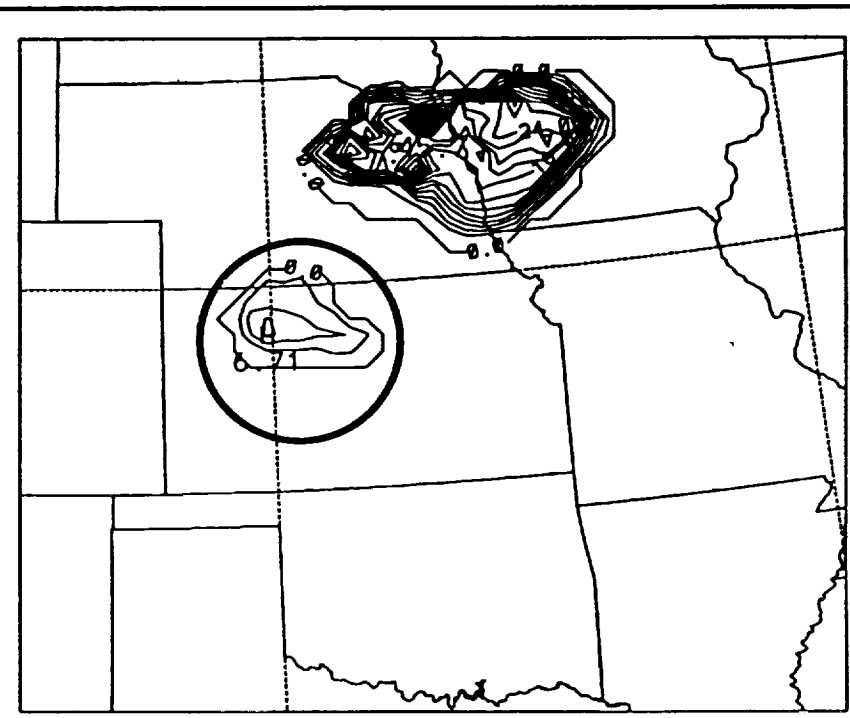
Example of convergent initial wind field at the surface triggering premature convection in the PRE-STORM area



divergence (negative areas dashed)

Note the strong convergence here due to convergent initial wind fields

The "bogus" convection in the prestorm area raised the soil moisture, inhibiting the diurnal heating in the PRE-STORM area. No MCS formed in this simulation



Accumulated convective precipitation

The contouring here shows where the parameterization has been active. Note the circled region of convective activity in the PRE-STORM region.

These plots are at 2.5 hours of simulation time, 8:30 AM local time

Fig. 11 2.5-hr RAMS model forecasts of surface divergence and convective precipitation fields for the 23-24 June 1985 PRE-STORM case.

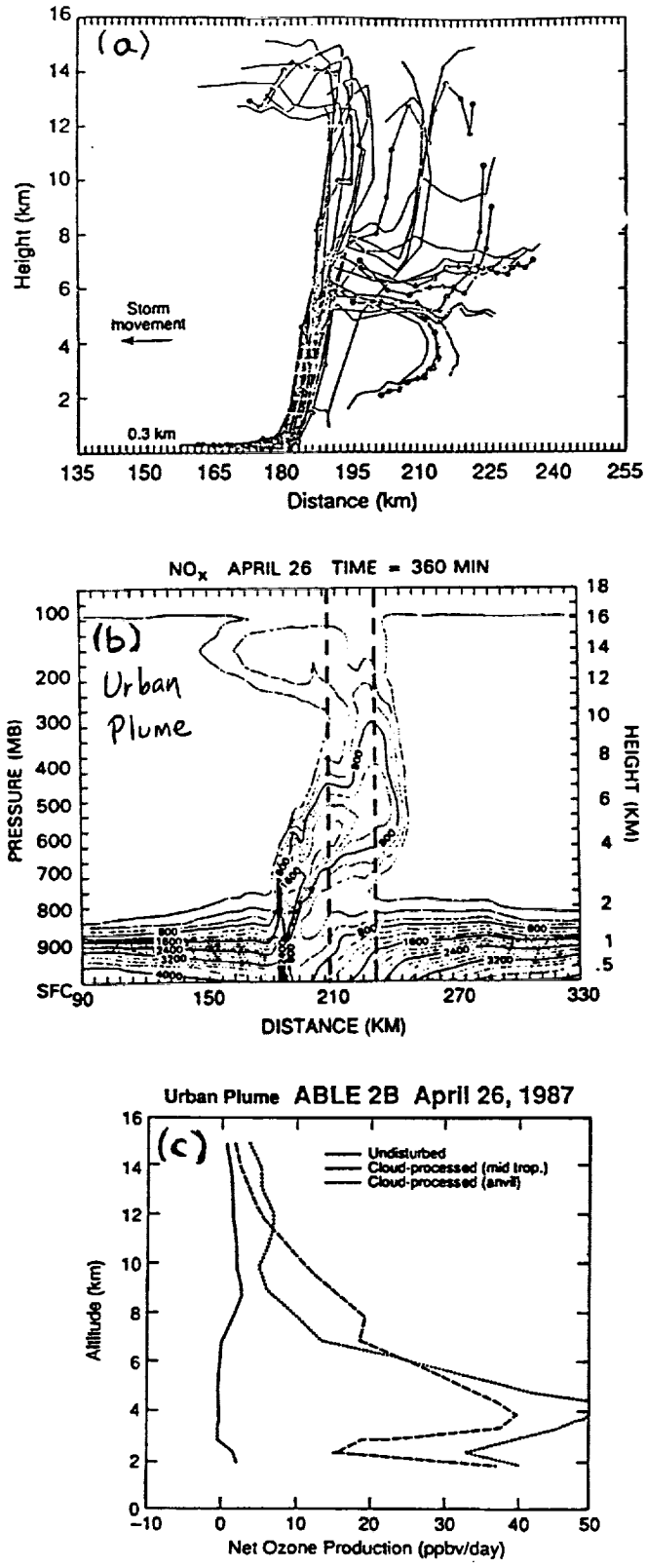


Fig. 12 Interaction of convection and trace gases from the 26 April 1987 convective squall line from GTE/ABLE 2B. (a) Forward trajectories from 0.3 km level show where air is transported and detrained during convection; (b) convective redistribution of NO_x from Manaus, Brazil, plume at end of 4 hours simulation with 2D cloud tracer model; (c) Effect of convection on O_3 photochemical production rate (24-hour integrated rate of O_3 formation) due to convection. Solid line represents O_3 formation in "undisturbed" air; dashed lines refer to O_3 formation based on cloud-processed NO_x profiles shown in (b). After Pickering et al. (1992c).

APPENDIX A:
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The Colloquium and Workshop on Multiscale Coupled Modeling was held for the purpose of addressing modeling issues of importance to planning for the Cooperative Multiscale Experiment (CME). Representatives from various meteorological programs expressed potential interest in collaborating together to achieve the unified purposes of the CME. The colloquium presentations addressed the current ability of numerical models to accurately simulate the development and evolution of mesoscale cloud and precipitation systems and their cycling of water substance, energy, and trace species. The workshop participants made recommendations for the improvement of mesoscale models prior to the CME, their coupling with cloud, cumulus ensemble, hydrology, and air chemistry models, and the observational requirements to initialize and verify these models. Mesoscale convective system (MCS) provide the focus of the CME. Most convective field experiments in the past have attempted to resolve only the immediate scales of moist convection using network arrays that spanned two or three atmospheric scales at most. This has precluded a description of the entire life cycle of MCSs and their interaction with larger scale systems, the land surface, and trace species. The workshop concluded that the time is right from a technical and observational perspective to conduct a multiscale field experiment focused on the mesoscale convection problem. The necessity for interdisciplinary activities in the CME involving the hydrology, ecology, and chemistry communities was also stressed. It was further suggested that linkages between CME and climate be emphasized, with regard to validation of model parameterizations and the upscale effects of MCS.

14. SUBJECT TERMS

Numerical weather prediction; Mesoscale convective system; Data assimilation; Parameterization; Mesoscale modeling

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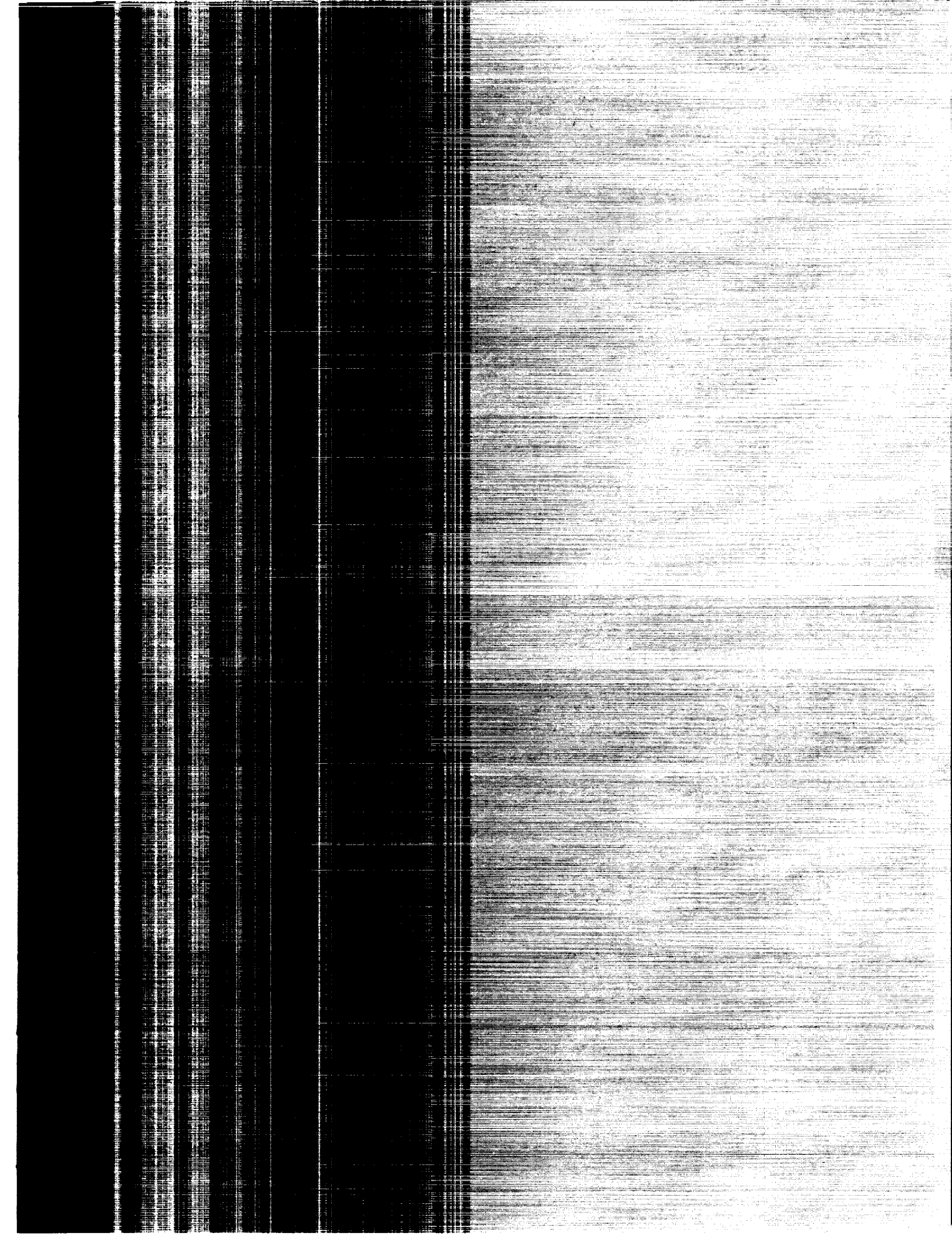

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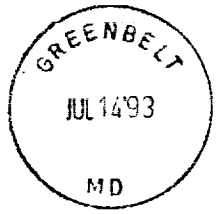

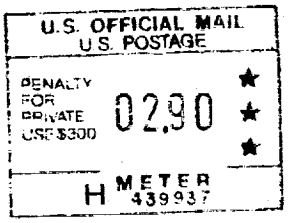

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